SELECTING DAM LOCATIONS IN THE SOUTHWESTERN REGION OF SAUDI ARABIA

BY

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Dedicated to my family and my Sir Abdullah Mohammod Zubair, executive engineer, project division-2, PWD, Bangladesh

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LIST OF ABBREVIATIONS

BCM : Billion Cubic Meters

CN : Curve Number

DW : Desalinated Water

FAO : Food and Agricultural Organization

HEC-HMS : Hydrologic Engineering Center's Hydrologic Modeling System

IPCC : Intergovernmental Panel on Climate Change

MCM : Million Cubic Meters

MOEP : Ministry of Economic and Planning of Saudi Arabia

MOWE : Ministry of Water and Electricity of Saudi Arabia

NGW : Non-renewable Ground Water

RGW : Renewable Ground Water

SCS : Soil Conservation Service

SWCC : Saline Water Conversion Corporation

TWW : Treated Waste Water

WMS : Watershed Modeling System

ABSTRACT

Full Name : [Muhaiminul Islam Fahmi]

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In 2014, total water demand in Saudi Arabia was around 16300 MCM (million cubic meters). The major portion of this demand was satisfied from groundwater sources. To date, a total of 465 dams have been constructed with the purposes of controlling floods, recharging shallow aquifers, supplying drinking water and using for agriculture in the country. The total capacity of these dams was estimated to be more than 2000 MCM. The desalination plants supply approximately 2080 MCM of desalinated water annually, which is primarily used for domestic purpose. Reuse of treated wastewater (TWW) has been in practice. However, only a fraction of TWW is being recycled for reuse. The country often experiences flash floods, particularly in the southwestern region, due mainly to heavy rainfall within a short period, which have been responsible for many deaths and property damage in the country. In this research, locations of new dams were identified in five areas (Abha, Al-Baha, Bisha, Jizan and Khamis-Mushait) in the southwestern region. The watershed delineation and runoff quantification were performed using the WMS (Watershed Modeling System) software and HEC-HMS hydrologic model respectively. The parametric uncertainty was incorporated through fuzzy rule based modeling. For the return period of 100 years, the average runoff in Abha, Al-Baha, Bisha, Jizan and Khamis

Mushait dams were estimated to be 30.4, 42.2, 4.9, 16.4 and 9.4 MCM per year respectively. Use of the runoff in these regions can save approximately US$ 34.6, 45.2, 7.8, 22.2 and 12.4 million per year respectively. This can also reduce the CO_2 emission of 481.8, 674.5, 96.7, 87.1 and 165.9 million kg per year respectively.

ملخص الرسالة

الاسم الكامل: موهيمين ال اسلام فهمي

عنوان الرسالة: اختيار مواقع السد في المنطقة الجنوبية الغربية من المملكة العربية السعودية

التخصص: قسم الهندسة المدنية والبيئية (الموارد المائية والهندسة البيئية)

تاريخ الدرجة العلمية: ديسمبر 2017

في عام 2014، بلغ إجمالي الطلب على المياه في المملكة العربية السعودية حوالي 16300 مليون متر مكعب MCM.) (إن الجزء الأكبر من هذا الطلب تم تلبيته عن طريق مصادر المياه الجوفية. وحتى الآن، تم بناء ما مجموعه 465 سداً بهدف السيطرة على الفيضانات، وإعادة شحن طبقات المياه الجوفية الضحلة، وتوفير مياه الشرب واستخدامها للأغراض الزراعية. وقدرت القدرة الإجمالية لهذه السدود أكثر من MCM 2000. وتوفر محطات التحلية ما يقرب من MCM 2080 من المياه المحلاة سنويا، والتي تستخدم أساسا للأغراض المنزلية. كما تم استخدام مياه الصرف الصحي المعالجة. ومع ذلك، من الملاحظ أنه لا يعاد تدوير سوى جزء صغير من مياه الصرف المعالجة لإعادة استخدامها. وكثيرا ما تشهد البلاد فيضانات مفاجئة، وخاصة في المنطقة الجنوبية الغربية، ويرجع ذلك أساسا إلى هطول الأمطار الغزيرة في غضون فترة قصيرة، والتي كانت مسؤولة عن العديد من الوفيات والأضرار في الممتلكات. وفي هذا البحث، تم تحديد مواقع السدود المقترحة في خمس مناطق (أبها، الباحة، بيشة، جازان وخميس مشيط) في المنطقة الجنوبية الغربية. تم تنفيذ ترسيم مستجمعات المياه وكمية الجريان السطحي باستخدام برنامج WMS (نظام نمذجة مستجمعات المياه) والنموذج الهيدرولوجي HEC-HMS على التوالي. تم تضمين عدم التيقن القياسي من خلال النمذجة القائمة على القواعد الرياضية. وبالنسبة لفترة العودة البالغة 100 سنة، قدر متوسط الجريان السطحي في أبها والباحة وبيشة وجيزان وخميس مشيط ب MCM 30.4 و MCM 42.2 و MCM 4.9 و MCM 16.4 و MCM 9.4 في كل سنة على التوالي. ويمكن أن يوفر استخدام الجريان السطحي في هذه المناطق ما يقرب من 34.6 مليون دولار ، و 45.2 مليون دولار ، و 7.8 مليون دولار ، و 22.2 مليون دولار ، و 12.4 مليون دولار في كل سنة على التوالي. وهذا يمكن أن يقلل أيضا من انبعاث ثاني أكسيد الكربون بنحو 481.8 مليون كجم، 674.5 مليون كجم، 96.7 مليون كجم، 87.1 مليون كجم و 165.9 مليون كجم في كل سنة على التوالي.

CHAPTER 1

INTRODUCTION

1.1 Background

Saudi Arabia is under a great threat of water scarcity [1]. Total water demand in Saudi Arabia was estimated to be 16300 million cubic meters (MCM) in 2014. In 2009, the demand was 18500 MCM, in which 84% was used for agriculture. The agricultural water demand was planned to reduce to 12800 MCM by 2014 [2]. From 2009 to 2016, water demand in domestic sector increased from 2123 MCM to 3129 MCM [3] and predicted to be 3268 MCM by 2020 [4]. By 2020, water demand in industrial sector is forecasted to be increased to approximately 1000 MCM [4].

In 2014, the water demand in Saudi Arabia were planned to be satisfied 83.5% from groundwater and surface water sources, 12.7% from desalinated water sources and 3.8% from treated wastewater sources [2]. The groundwater includes renewable (RGW) and non-renewable (NGW) sources [5]. The proven, probable and possible reserves of NGW in Saudi Arabia were 253.2, 405 and 705 billion cubic meters (BCM) respectively [6]. The annual recharge rate to the aquifers is only 1.3 BCM [7], where 30% water drains out yearly from the Kingdom to the neighboring countries through underground [5].

In Saudi Arabia, many dams are constructed specially in the southwestern region with the goal of storing runoff water as well as for flood protection [8]. Overall, 465 dams are constructed in the country with the capacity of more than 2000 MCM water to collect, store and recharge aquifers and to control floods [9]. A total of 166 dams with capacity of more than 760 MCM are located in southwestern region [9]. The long-term average rainfall in the country was estimated to be less than 70 mm/year, whereas in the southern region, 500 mm rainfall is not uncommon [6]. In the southern region, heavy rainfall creates frequent flash floods which indicates the needs for additional dams instead of having ample numbers of dams already built there [10].

Past studies have recommended the collection and use of runoff as a partial solution to the water crisis problems in the domestic, agriculture and industrial sectors. The present study identifies the locations of five new dams in five areas (Abha, Al-Baha, Bisha, Jizan and Khamis Mushait) of the southwestern region of Saudi Arabia. This will assist in better understanding of the locations of new dams, the runoff volume as the potential sources of water, cost saving through using the runoff and the reduction of CO_2 release into the environment.

1.2 Study Region

The Kingdom of Saudi Arabia is the second largest country in the Arab world with the area of approximately 2.2 million square kilometers [11]. The country is situated between the coordinates of 16.5°N - 32.5°N latitude and 33.75°E - 56.25°E longitude. Saudi Arabia has borders with the Red Sea to the west and the Arabian Gulf to the east. About 90% of total area of Saudi Arabia is covered by deserts and plain lands [12]. The current population in the country is around 32 million [13], which are growing at the rate of 2.6% per year [14].

The present study aims to find locations for new dams in five areas from the southwest region of Saudi Arabia. The areas are: Abha, Al-Baha, Bisha, Jizan and Khamis Mushait (Figure 1.1).

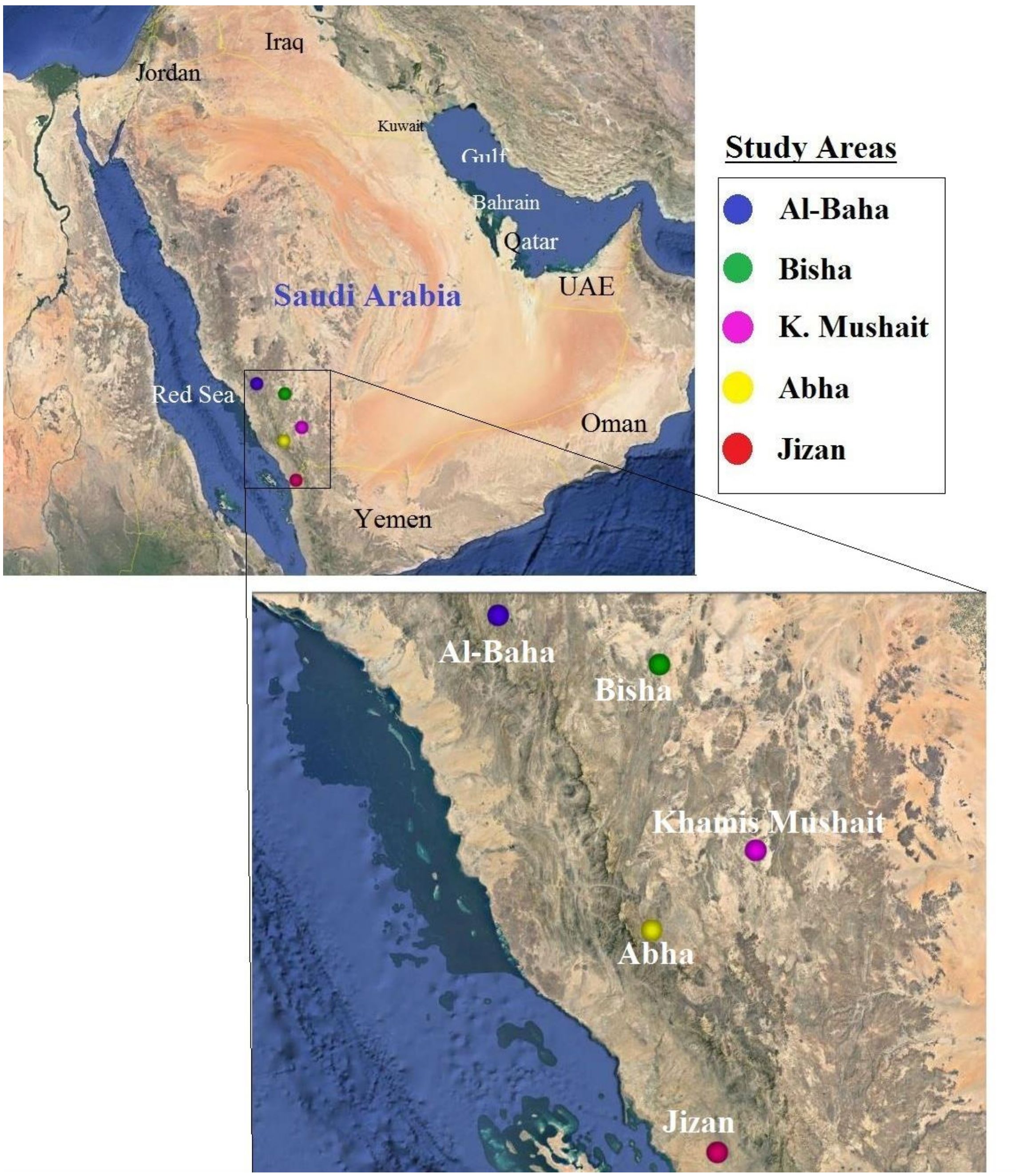


Figure 1.1: Locations of the areas under study

The southwestern region of Saudi Arabia is mountainous, relatively high in elevation and experiences the maximum yearly rainfall [6]. The rainfall is influenced by the subtropical and orographic conditions [15]. The areas of Abha, Khamis-Mushait and Bisha are influenced by the southeastern moist air and receive the maximum rain through half of the year, probably due to the increase of rainfall in the leeward side of mountain [10]. The periods of rainfall in Al-Baha and Jizan are different than the other areas [10].

Abha is the capital of Asir region. This area is approximately 2200 meter above the mean sea level, surrounded by mountains, valleys and plain lands [16]. It experiences occasional heavy rainfall with yearly average rainfall of approximately 215 mm [17]. The rainfall of up to 400 mm was reported in the coastal side or over the mountains of Abha [16]. The mean annual temperature is 18.3^{o}C with the maximum of 32^{o}C in July. The minimum temperature is observed usually in January and the lowest temperature was recorded to be -3^{o}C [16].

Khamis-Mushait is in the east of Abha, surrounded by valleys and agricultural farms [18] with a land area of 1075 km^2 [19]. The mean yearly precipitation is approximately 193 mm [17] and the maximum rainfall was observed in the month of May with more than 38 mm [20]. The minimum temperature was observed 4.4^{o}C in January and maximum 38^{o}C in July, measured in 2012 [21].

Bisha is in the north of Khamis-Mushait. The mean annual precipitation was around 88.7 mm [22]. The maximum rainfall was observed in the month of April with approximately 34 mm [23]. In 2012, the minimum Temperature was observed in January with 3.8^{o}C and maximum in July with 43^{o}C [21].

The most northern location of this study is Al-Baha. Al-Baha is very high in elevation (up to 2565 meter from mean sea level) [24]. Average precipitation of this area is 139 mm/year [17]. The maximum rainfall is observed in the month of April with approximately 35 mm [23]. The climate is comparatively cold in winter with minimum 10^{o}C temperature and mild in summer with maximum 32^{o}C [25].

Jizan is situated in the extreme southwest corner of Saudi Arabia. The annual average precipitation is approximately 140 mm [17] and the maximum rainfall was observed in the month of October with approximately 19 mm [23]. According to the temperature data collected by Presidency of Meteorology & Environment (PME) the minimum temperature in Jizan was observed very hardly below 20^{o}C in the winter season in the last 18 years, which indicates a warmest winter among the five study areas [21].

1.3 Problem Definition and Justification

The total internal renewable fresh water resource in Saudi Arabia was estimated to be approximately 2.4 BCM [6]. However, consumption of freshwater was estimated as 18.5 BCM in 2009 [2] and predicted to be 26.6 BCM in 2050 [26]. Per capita renewable fresh water resource in Saudi Arabia is less than 25% from the global average [27]. The major sources of fresh water in Saudi Arabia are; groundwater, desalinated water, treated wastewater and surface water. The groundwater includes the renewable (RGW) or non-renewable (NGW) sources. About 83.5% of total water demand is fulfilled from these two sources [2]. The total proven amount of NGW is approximately 253.2 BCM [6]. The annual recharge rate to this these aquifers is only 1.3 BCM [7], where 30% of the water drains out (as base flow) from the country [5].

To conserve groundwater, the country is in the process of suspending the major agricultural activities and increasing the production of desalinated water and reuse of treated wastewater. In the Ninth Development Plan, the desalinated water was planned to be doubled from 2009 to 2014 (from 1048 MCM to 2070 MCM) [2]. Saline Water Conversion Corporation (SWCC) alone produced 1247.9 MCM desalinated water in 2015, which was 60% of the country's total production, that infers country's total production of desalinated water was 2080 MCM [28]. The conventional desalination processes, such as distillation and reverse osmosis processes, consume a large amount of oil based energy, which is responsible for carbon-di-oxide (CO_2) emission into the environment [29]. The range of CO_2 emission varies from 3.4 to 25 kg-CO_2/m^3 of desalinated water depending on the process and fuel used [30]. Saudi Arabia emitted approximately 412 million ton of CO_2 (MT CO_2) in 2005 [31] and 472.19 MT CO_2 in 2010 [27]. By 2020 the total carbon emission is projected to be 750 MT CO_2, which will pull the country to the top of the carbon emission countries [32]. In 2010 the country emitted 54.19 MT CO_2 from desalination plants which was 12% of the total carbon emission in that year [27]. Indeed, it is high time for the country to move towards the natural and renewable sources of freshwater, such as, collection and use of runoff.

The runoff generated from seasonal rainfall is the only source of surface water (SW) in Saudi Arabia. In the northern region, annual rainfall varies from less than 100 mm to maximum 200 mm, whereas in the southern region, up to 500 mm rainfall is not unusual [6]. The long-term average rainfall in the country was estimated to be approximately 70 mm/year, in which most of this rainfall occurs in the south and southwestern regions of the country [6], which is likely to provide an opportunity to collect and use runoff from this region.

During heavy rainfall, chances of natural infiltration develops. The sudden intense rainfall for a relatively shorter duration leads to flash flood and high runoff over wadies. Dams are needed to cease the flow and to increase the vertical head, which can help in natural infiltration [33]. In the country, many dams are constructed in the southwestern region with the goal of storing water from runoff [8]. A total of 166 dams with capacity of more than 760 MCM are located in this region [9]. Overall, 465 dams are located in the country with the capacity of more than 2000 MCM water. The purpose of the dams are to collect, store and recharge aquifers, and to control floods [8]. Despite the large number of dams, frequent flash floods in the southwestern region indicate the needs for additional dams [10]. Al-Zahrani et al. (2015) demonstrated the loss of significant amount of runoff in this region, due mainly to inadequate capacities, inappropriate locations and lack of maintenance of the dams [10]. The present study identifies the locations of five new dams in the southwestern region, which are likely to save significant amount of runoff. The runoff can be infiltrated through natural or forced infiltration, which can be used for the domestic, agricultural or industrial purposes. Use of the natural water sources will lessen the pressure on non-renewable groundwater sources while this can save money and the environment.

1.4 Objectives

The main objective of this research is to quantify the runoff generations and to identify the possible locations of dams to collect runoff in five areas (Abha, Al-Baha, Bisha, Jizan and Khamis-Mushait) in the southwestern region of Saudi Arabia. The main objective will be achieved through achieving the following.

i. Quantifying runoff generations in five areas (Abha, Al-Baha, Bisha, Jizan and Khamis-Mushait) in the southwestern region of Saudi Arabia from the storm event with 25, 50 and 100 years return period.
ii. Predicting runoff variability due to data uncertainty in different parameters, including rainfall depth, soil type, land use, curve number etc. using the fuzzy set concept.
iii. Comparing the cost and reduction of carbon emissions in context to desalinated water use.

1.5 Organization of Thesis

The present thesis is organized into five chapters. The summary of the chapters are presented below:

Chapter 1 presents the introduction of the thesis. The background of the present study, problem definition and justification and the objective of the study are described here.

Chapter 2 presents the available water resources in Saudi Arabia, impact of desalination process on climate change, dams in Saudi Arabia, modeling and uncertainty analysis in water resources.

Chapter 3 presents the methodologies of data collection, software use and uncertainty analysis. The methodology of cost saving and carbon reduction estimation is also presented in this chapter.

Chapter 4 describes the procedure of selecting the locations for the new dams and the computation of the flow data and curve numbers.

Chapter 5 presents the results for the five areas. The findings for each region are discussed and summarized in this chapter.

Chapter 6 presents the conclusion and recommendations for future research.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

The climate of Saudi Arabia is characterized by arid and semi-arid conditions with low annual rainfall. In 2009 and 2014, the annual water demands of the Kingdom were 18500 MCM and 16300 MCM respectively [2]. The country has limited groundwater reserves that are continuously under increasing demand. There is no natural surface water flow system in the country. Saudi Arabia is heavily dependent on the groundwater resources as well as on the desalination of sea water [12]. The seasonal rainfall events are important for the natural replenishment of shallow aquifers [22]. In the country, a total of 465 dams were built to augment the water resources through collecting the runoff. However, past studies reported that the total estimated reserves and contributions through annual recharges might not be adequate to satisfy the needs of the country in future [34].

2.2 Water Resources in Saudi Arabia

The major sources of fresh water in Saudi Arabia are; groundwater, surface water, desalinated water and treated wastewater. The groundwater includes renewable (RGW) or non-renewable (NGW) sources [5].

Past studies have indicated that the proven, probable and possible reserves of NGW in Saudi Arabia were 253.2, 405 and 705 BCM respectively [6]. Another study estimated this reserve with a range of 259.1 –760.6 BCM [4]. The annual recharge to these aquifers was estimated to be 1.3 BCM [7] and the total internal renewable water was estimated to be 2.4 BCM [4]. It is likely that significant fraction of this water might have been used in the past [8], [35]. Overexploitation of fossil groundwater resources affects the aquifer's productivity in terms of quantity and quality.

The source of surface water is the seasonal rainfall [5]. Al Yamani and Sen studied the seasonal variability of rainfall in Saudi Arabia using the monthly data for 15-years [36]. The maximum rainfall in the southwestern region was recorded in January along with other maxima in February and October in the central regions. The southwest region received high rainfall, which decreased towards the east [12]. In the northern regions of Saudi Arabia, annual rainfall ranged between less than 100 mm to 200 mm, while in the south, annually 500 mm rainfall was not unusual [6]. The long-term average rainfall in the country was estimated to be less than 100 mm/year [6]. Approximately 60% of the total runoff occurs in western region where the area represents only 10% of the country, while the remaining 40% occurs in the extreme south of the western coast (Tihama), which covers approximately 2% of the total area [6]. A recent study predicted the increase of rainfall in the eastern, western, central and southern parts of Saudi Arabia by 2050 [34]. However, a major fraction of rain water is evaporated [37].

In Saudi Arabia, reuse of treated wastewater (TWW) for agriculture is in practice to a limited scale [38]. The wastewater treatment plants (WTP) primarily serve for the large and medium-size cities [39]. In 2009, approximately 730 MCM of domestic wastewater was treated while 325 MCM was recycled for reuse [40]. In 2014, domestic wastewater production was estimated to be 1546 MCM [41], in which about 1260 MCM was treated.

Currently, domestic wastewater is treated in about 81 sewage treatment plants, which has the capacity to treat approximately 1730 MCM per year [8]. However, wastewater generation was reported to be more than this capacity [8]. The un-used TWW and domestic wastewater are generally discharged into the Arabian Gulf, Red Sea, sand dunes and through the un-protected septic pits, which is likely to degrade the quality of the groundwater. The Kingdom is considering the full use of TWW by 2025 [39]. However, appropriate strategy is needed to assess the feasibility of reusing TWW and the scopes of their applications.

The Kingdom of Saudi Arabia is the largest producer of desalinated water as a single country [42]. In 2004 and 2009, the production of desalinated water was approximately 1070 MCM and 1048 MCM respectively, which was planned to be almost doubled by 2014 with 2070 MCM [2]. Saline Water Conversion Corporation (SWCC) alone produced approximately 1248 MCM of potable water in 2015 from its 28 desalination plants in the coasts of the Arabian Gulf and Red Sea [28]. That amount was approximately 60% of the total desalinated water production of the country, which estimates country's total desalinated production in 2015 was 2080 MCM [28]. In 2014, SWCC had the capacity of producing 58% of country's total desalinated water, while the remaining 42% was for the private plants [43]. The desalinated water fulfils more than 70% of total domestic water demand in the country [8].

2.3 Impact of Desalination Process on Climate Change

Saudi Arabia is burning approximately 500,000 barrels of oil per day to satisfy the energy demands in the country [32] while about half of the domestic oil consumption is due to the desalination plants [1]. The fossil fuel consumption in the desalination plants is expected to increase in future [44]. The production of 1 m^3 of desalinated water requires approximately 25 kg of oil [45]. In Saudi Arabia 54.2 million ton CO_2 (MT CO_2) is emitted from desalination plants per year [27]. The increased use of fossil fuels for desalination is likely to accelerate air pollution through greenhouse gas emissions [46]. Desalination plants also utilize significant amounts of chemicals for pre-treatment of saline water and post-treatment of desalinated water. Discharge of large amounts of chemicals into the coastal waters may result in ecological imbalances [47], [48].

2.4 Dams in Saudi Arabia

In Saudi Arabia, dams are used for the purposes of:

I. Recharging the shallow aquifers to provide the wells with water in the agricultural regions.
II. Securing potable water for some regions.
III. Securing irrigation water for farming purposes through direct irrigation for farmlands.
IV. Protecting the cities and villages from the risks of flash floods [42].

The total surface runoff generation in Saudi Arabia was estimated to be 2.2 BCM/year [6]. In the southwest region, dams have been constructed to collect runoff and increase the vertical head for enhanced infiltration [33]. The wadi reservoirs, which are built attached to a reservoir dam, can add a significant quantity of recharge to the aquifer system. However, the evaporative loss can range from 5 to 80% of the water [37], [49].

In 2009, Saudi Arabia had 223 dams, which served for purposes with the total storage capacity of 835.6 MCM [42]. In 2012, approximately 1.4 BCM/year of runoff was stored by 302 dams across Saudi Arabia, from which 992.7 MCM was recharged to the shallow aquifers, 303.5 MCM was used for drinking and 51.5 MCM was used for agriculture [4]. In present, a total of 465 dams with capacity of collecting and storing more than 2000 MCM of runoff is supporting the water resources augmentation program in Saudi Arabia [9]. About 60% of the total runoff is generated in the southwestern region [33]. In this region, there are 166 dams with capacity of more than 760 MCM [9]. Despite the large number of dams, frequent flash floods in the southwestern region indicate the needs for additional dams in the country [10]. Al-Zahrani et al. (2015) demonstrated the loss of significant amount of surface runoff in this region, due mainly to inadequate capacities, inappropriate locations and lack of maintenance of the dams. Further, the silt and clay carried by runoff is deposited in the bottom of the stagnant water [33]. Moreover, up to 80% of the stored water was reported to be lost due to evaporation from free surface [33]. Immediate recharge following the runoff collection can be an option to minimize evaporation loss [50].

The urbanization through the construction of impervious surfaces, building, roads, storm sewers and pavements usually decreases the infiltration capacities and increases runoff. In completely impervious areas where ground is fully facilitated with sewer system, peak discharge increases to 6 times more than in non-urbanized areas [51].

2.5 Use of Modeling Software in Water Resources

Past studies have modelled floods in Saudi Arabia (e.g., [52], [53], [54]), where WMS software was used. The HEC-HMS (Hydrologic Engineering Center's Hydrologic Modeling System) hydrologic model was used in the main channel of Wadi Fatimah watershed in the western Saudi Arabia to monitor hydrologic responses through dividing the watershed into seven sub-basins [55]. The return periods were 10, 25, 50 and 100 years and the rainfall duration was 1 hour. Flood simulations were performed using the WMS software for several return periods in the Almisk Lake stretched along Wadi Bani Malek in Jeddah. The HEC-HMS software was employed to compute the peak flow [52]. Another study evaluated the flash flood hazard in the Wadi Qanunah basin, which is in the southwestern coast of Makkah, Saudi Arabia. The basin was divided into 13 sub-basins using WMS software. HEC-HMS software was used to generate hydrographs for two sub-basins of Wadi Qanunah. The rainfall events with return periods of 5, 10, 25, 50 and 100 years were considered. Total volume of discharge in the Wadi Qanunah sub-basins were in the ranges of 66 - 138 MCM [56].

2.6 Uncertainty Analysis in Water Resources

The mathematical precise solutions are generally insufficient to represent the real-life problems where data are imprecise. To analyze uncertainties, a widely used approach is the Monte Carlo (MC) simulation, which requires precise data to generate statistical distributions [57].

The MC simulation uses statistical distributions in characterizing uncertainties. In this process low probability parameter values do not have equal chances to be randomly selected [57], [58]; thus, a portion of extreme possibility might be overlooked. In contrast, fuzzy logic combines all possible parameter values through membership grades [57]. This method enables the incorporation of imprecise data where information is limited, qualitative or sparse, which provides an advantage over some other uncertainty characterization approaches. A fuzzy set establishes the relationship between uncertain data and the membership function μ, which ranges from 0 to 1 [38].

The hydrological data are typically limited and sparse, and it is often difficult to develop the appropriate statistical distributions for these data [59]. In the arid regions, rainfall events can be intensive during the storms while during the other periods, rainfall can be very low [12]. Application of fuzzy sets in characterizing the uncertainty is likely to appropriate in this context.

CHAPTER 3

METHODOLOGY

This study identifies locations for new dams in five areas in the southwest region of Saudi Arabia. This study estimated the potential runoff using the Watershed Modeling System (WMS) software and compared the saving of cost and carbon release from the desalination process. The details of the methodology are presented below.

3.1 Data Collection

3.1.1 Rainfall Data Collection

Using the historical rainfall data from 1985-2009, past studies have developed the IDF curves for 2, 5, 10, 25, 50 and 100 years of return periods for Abha, Al-Baha, Bisha, Jizan and Khamis-Mushait. The IDF curves were developed using different methods of daily rainfall depth conversion and a range of rainfall depth was obtained for a return period. Table **3.1** shows the rainfall variability for different rainfall intensities and durations for regions under investigation. The ranges of rainfall depths in different return periods allow the prediction of surface runoff with rainfall variability. As such, uncertainty related to rainfall depth was incorporated. For this study, to be safe from deluge the maximum values from the range of rainfall depths were used as the most likely input parameter and uncertainty was incorporated later. The IDF curves for five areas with most likely rainfall depths are presented in Figure **3.1** - Figure **3.5**. The storm pattern was assumed as SCS (Soil Conservation Service) Hypothetical Storm - Type II, which represents the storm pattern in the arid/semi-arid regions [60].

Table 3.1: Rainfall intensities (mm/hour) for specific duration at different return periods

Name of regions	Rainfall duration (minute)	Rainfall intensities (mm/hour)											
		2 years		5 years		10 years		25 years		50 years		100 years	
		min	max	min	Max	min	max	min	max	min	max	min	max
Abha	10	45.5	75	79.6	131.4	102.3	168.8	130.9	215.9	152.1	250.9	173.2	285.7
	30	25.8	42.4	45.1	74.3	58	95.5	74.2	122.2	86.2	142	98.1	161.6
	60	16.7	25.8	29.2	45.1	37.5	58	48	74.2	55.8	86.2	63.5	98.1
	120	10.8	15	18.9	26.2	24.3	33.7	31.1	43.1	36.1	50.1	41.1	**57**
Al-Baha	10	35.6	58.8	67.1	110.8	88	145.2	114.4	188.8	134	221.1	153.4	253.1
	30	20.2	33.2	38.1	62.7	49.9	82.2	64.8	106.8	75.9	125	86.9	143.2
	60	13.1	20.2	24.6	38.1	32.3	49.9	42	64.8	49.1	75.9	56.2	86.9
	120	8.5	11.7	16.0	22.1	20.9	29	27.2	37.7	31.8	44.1	36.4	**50.5**
Bisha	10	25.2	41.7	37.3	61.5	45.3	74.7	55.4	91.5	62.9	103.9	70.4	116.2
	30	14.3	23.5	21.1	34.8	25.7	42.3	31.4	51.7	35.7	58.8	39.9	65.7
	60	9.2	14.3	13.7	21.1	16.6	25.7	20.3	31.4	23.1	35.7	25.8	39.9
	120	6.0	8.3	8.9	12.3	10.8	14.9	13.2	18.2	15	20.7	16.7	**23.2**
Jizan	10	45.3	74.7	69.5	114.8	85.6	141.3	106	174.8	121	199.7	136	224.4
	30	25.6	42.2	39.4	64.9	48.5	79.9	60	98.9	68.6	113	77.1	126.9
	60	16.6	25.6	25.5	39.4	31.4	48.5	38.9	60	44.4	68.6	49.9	77.1
	120	10.8	14.9	16.5	22.9	20.3	28.2	25.2	34.9	28.7	39.8	32.3	**44.8**
Khamis Mushait	10	36.6	60.5	59.6	98.4	74.9	123.5	94.1	155.3	108.4	178.8	122.6	202.2
	30	20.8	34.2	33.8	55.7	42.4	69.9	53.3	87.8	61.4	101.2	69.5	114.4
	60	13.4	20.8	21.9	33.8	27.5	42.4	34.5	53.3	39.7	61.4	44.9	69.5
	120	8.7	12.1	14.2	19.6	17.8	24.6	22.4	31	25.7	35.7	29.1	**40.3**

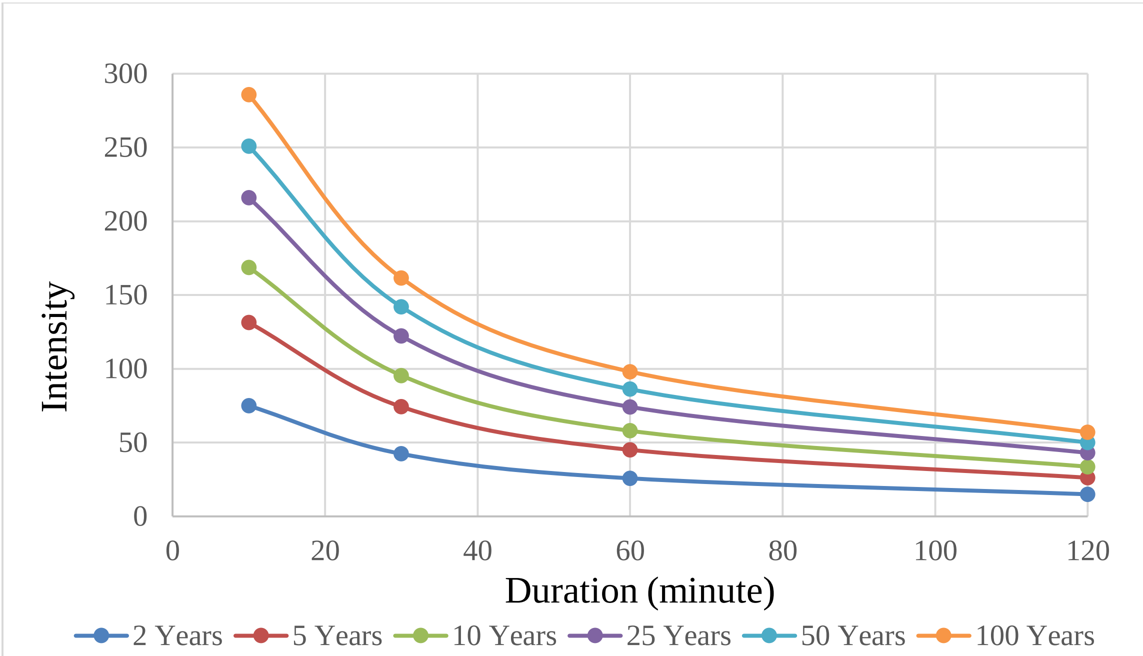


Figure 3.1: IDF curves for Abha watershed (maximum rain)

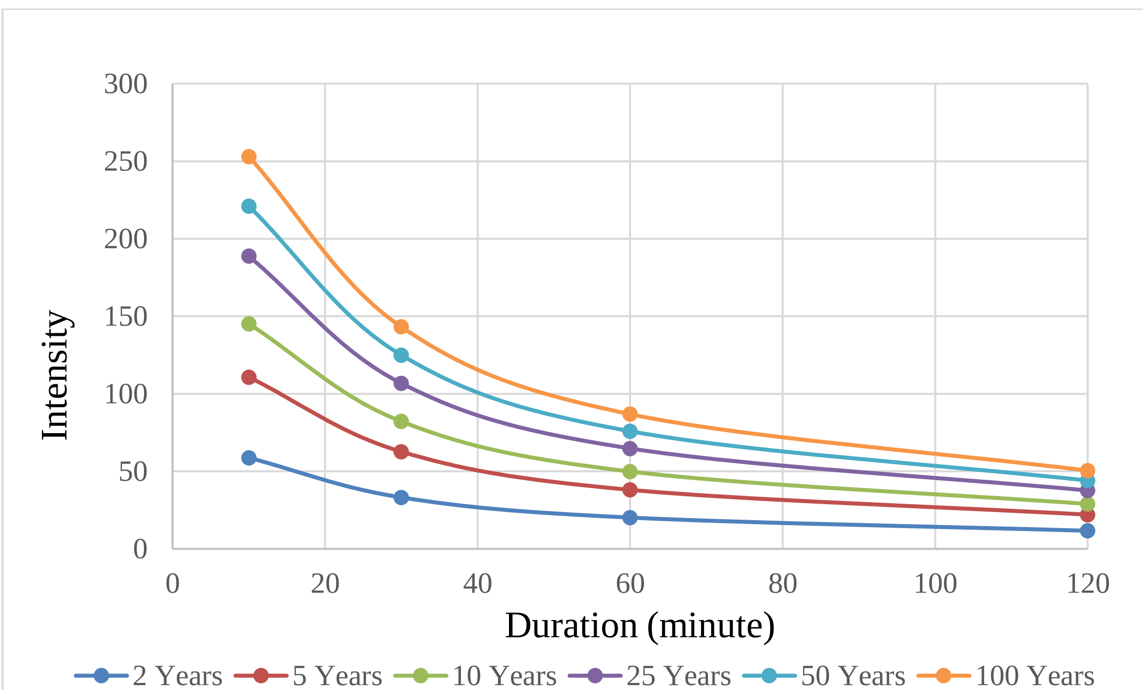


Figure 3.2: IDF curves for Al-Baha watershed (maximum rain)

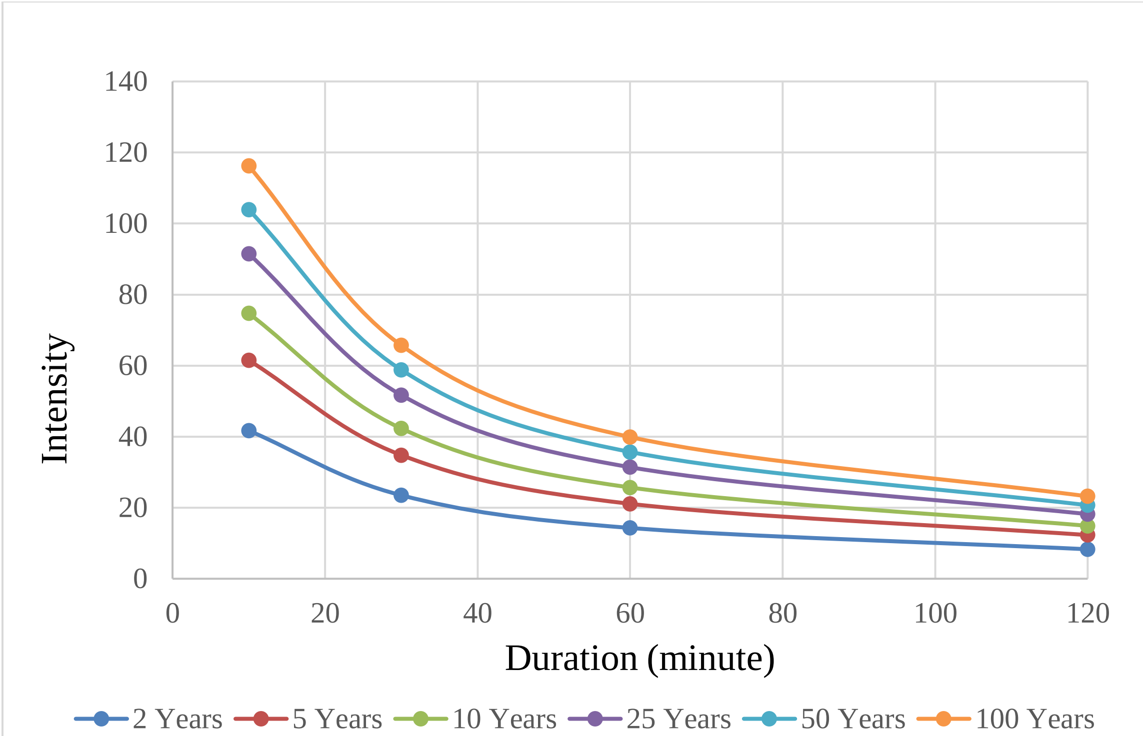


Figure 3.3: IDF curves for Bisha watershed (maximum rain)

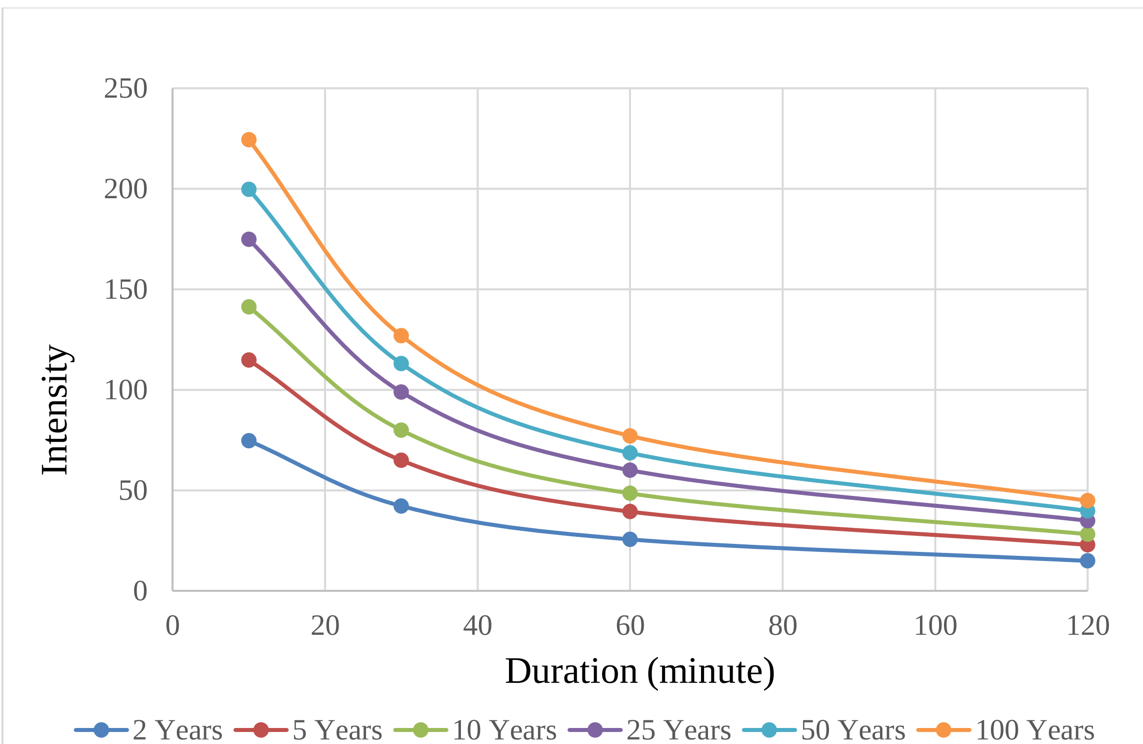


Figure 3.4: IDF curves for Jizan watershed (maximum rain)

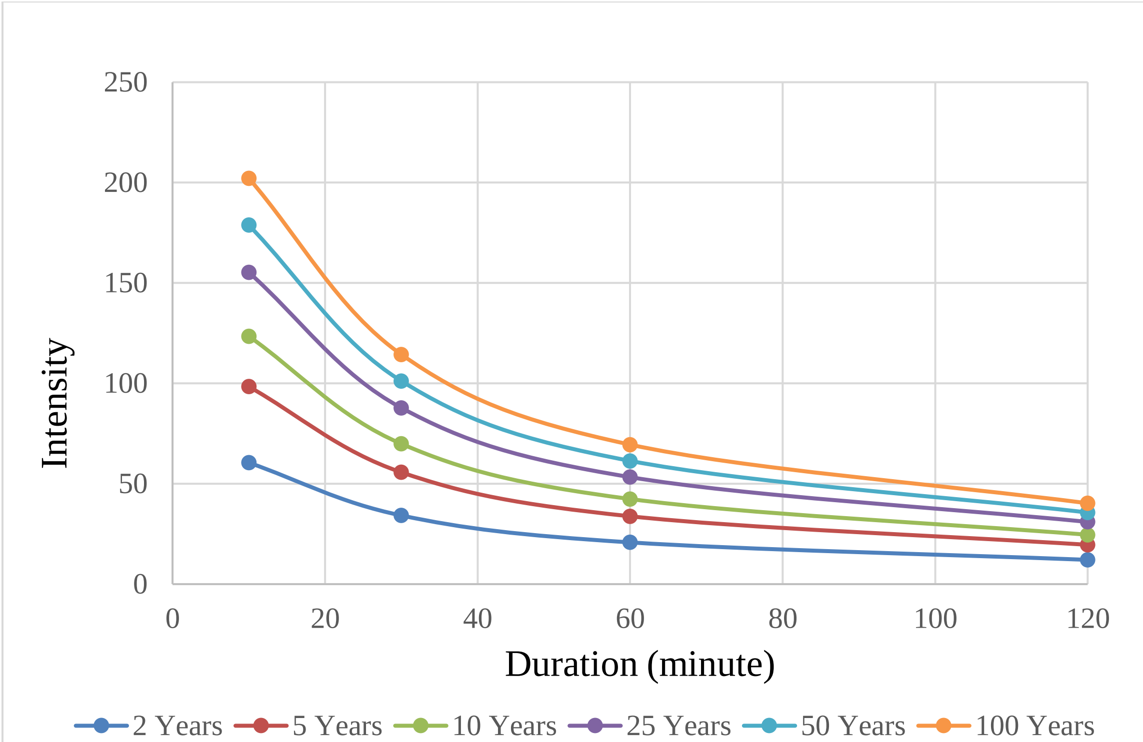


Figure 3.5: IDF curves for Khamis-Mushait watershed (maximum rain)

3.1.2 DEM Data Collection

The DEM (Digital Elevation Model) data were downloaded from SRTM (Shuttle Radar Topography Mission) Worldwide Elevation Data (3 arc second resolution) database. SRTM digital elevation data was developed by National Aeronautics and Space Administration (NASA). It has a resolution of 90 m at the equator, and is provided in mosaiced 5º × 5º tiles. It was downloaded through WMS Software.

3.1.3 Soil Type Data Collection

Soil type data were collected from Harmonized World Soil Database (version 1.1). The publisher of the database was International Institute for Applied Systems Analysis

(IIASA) and Food and Agricultural Organization (FAO). There are four soil index variables in the dataset, while soil is thoroughly wetted [61]:

- HSG (Hydrologic Soil Groups) Group A: Soils with high infiltration rates and low runoff potential.
- HSG Group B: Soils with moderate infiltration rates.
- HSG Group C: Soils with slow infiltration rates.
- HSG Group D: Soils with very slow infiltration rates and high runoff potential.

3.1.4 Land Use Pattern

Land Use Pattern data were collected from the Global Land Cover database and downloaded through WMS software. The data were derived from an automatic and regionally tuned classification of a time series of MERIS FR (Medium Resolution Imaging Spectrometer Full Resolution) composites. It covers the period from December 2004 to June 2006.

The mentioned data for the soil type and land use pattern were used only when the data from the past studies were not available.

3.2 Software Use

The WMS software was used to delineate the catchment areas. WMS is a two-dimensional modeling software, which deals with water quantity in watershed. WMS is widely used in delineating watershed and computing several hydrologic parameters, such as; CN (Curve Number), lag time, time of concentration, etc. [62]. WMS software includes several hydrologic and hydraulic models, including HEC-1 (Hydrologic

Engineering Center-1), HEC-RAS (Hydrologic Engineering Center's River Analysis System), GSSHA (Gridded Surface & Subsurface Hydrologic Analysis), HEC-HMS (Hydrologic Engineering Center's Hydrologic Modeling System) and others. WMS software works through the following steps:

- Delineating the watershed
- Single/multiple basin analysis by selecting a specific model
- Computing the Curve Number using land use and soil data
- Computing Lag time

In this study, the HEC-HMS (Hydrologic Engineering Center- Hydrologic Modeling System) hydrologic model will be used for predicting the surface runoff from the watersheds.

The delineated watershed from the WMS software is used by the HEC-HMS software and it generates the Direct Runoff Hydrograph (DRH). In HEC-HMS software, rainfall can be generated from a frequency-based hypothetical storm. Another way of generating rainfall is to consider the higher limit of rainfall as the storm event.

To compute the DRH with a Unit Hydrograph (UH), HEC-HMS uses the discrete form of rainfall excess, where each pulse of rainfall excess is known for each time interval. The discrete convolution equation is solved here for a linear system:

$$\boldsymbol{X_n = \sum_{m=1}^{n \le M} R_m U_{n-m+1}} \tag{1}$$

Where, X_n = ordinate of storm hydrograph at time $n\Delta t$,R_m= depth of excess rainfall in time interval $m\Delta t$ to $(m+1)\Delta t$, M = total number of discrete rainfall pulse and U_{n-m+1}

= ordinate of unit hydrograph at time $(n - m + 1)\Delta t. X_n$ and R_m are expressed as flow rate and depth respectively. The dimension of U_{n-m+1} is expressed as flow rate per unit depth.

The following assumptions were made in the HEC-HMS software:

- The excess rainfall is distributed uniformly and its intensity is constant during a time interval (Δt)
- The ordinates of a DRH corresponding to rainfall excess of a given duration are directly proportional to the volume of rainfall excess.
- The DRH is independent of the time of occurrence of the rainfall excess.
- Rainfall excesses of equal duration produce hydrographs with equivalent time bases [63].

3.2.1 Computation

3.2.1.1Delineating Basin

For each area, the watersheds were delineated by delineating flow paths using the Topographic Parameterization Program (TOPAZ) function. TOPAZ processes the DEM elevation data, delineate and order the basins and streams. It assumes that all depressions in the DEM are function of lack of resolutions.

3.2.1.2Curve Number

The CN (Curve Number) based method is used for estimating runoff from rainfall excess [64]. This method was developed by the USDA (United States Department of Agriculture) Natural Resources Conservation Service, which was known as the SCS (Soil

Conservation Service) method. The CN varies in the range of 30 to 100, where lower CN values indicate low runoff potential and high soil permeability and higher CN values indicate high runoff potential. CN value is computed as a function of soil type, land use and existing soil moisture for a watershed. Technical report (TR-55) of SCS consists the detail classification for these variables in tabular form [64]. Composite CN value for a watershed is computed using these tables and the collected information about the soil type and land use of the study area, using the following formula:

$$\mathbf{CN_{composite}} = \frac{\sum \mathbf{A_i CN_i}}{\sum \mathbf{A_i}} \tag{2}$$

Here, A_i is the area for the uniform curve number of CN_i. For *i* time variation of CN in a watershed, A_i time subdivided area will be found [63].

3.2.1.3Compute Lag Time

Time between the center of mass of the effective rainfall hyetograph and the center of mass of the direct runoff hydrograph is called Lag Time [65]. The Lag Time is calculated using the SCS method as:

$$\text{Lag time (hour)} = \boldsymbol{L}^{\mathbf{0.8}} \times \frac{\left\{\left(\frac{\mathbf{1000}}{\boldsymbol{CN}} - \mathbf{10}\right) + \mathbf{1}\right\}^{\mathbf{0.7}}}{\mathbf{1900} \times \sqrt{\boldsymbol{Y}}} \tag{3}$$

Where, CN = SCS curve number, L = Watershed length (ft), Y = Watershed slope in percent (%).

3.2.1.4Computation of Runoff

In HEC-HMS software runoff is calculated using Equation (1), where R is estimated as:

$$R = \frac{(P-0.2S)^2}{(P+0.8S)} \qquad (R = 0 \; if \; P < 0.2S) \tag{4}$$

Where, R = Precipitation excess (mm), P = Cumulative precipitation (in mm), S = Potential maximum retention (in mm) = $25.4\times\left(\frac{1000}{CN} - 10\right)$, CN = SCS curve number.

3.3 Runoff Generation

3.3.1 Preparing WMS file

In the WMS, the HEC-HMS hydrologic model was selected for simulation. In Meteorological Data, the Precipitation Method was selected as SCS Hypothetical Storm - Type II, which is representative to the semi-arid regions [66]. After inserting the necessary basin parameters, the file was saved and was processed in the HEC-HMS (Version 3.5) software (Figure **3.6**).

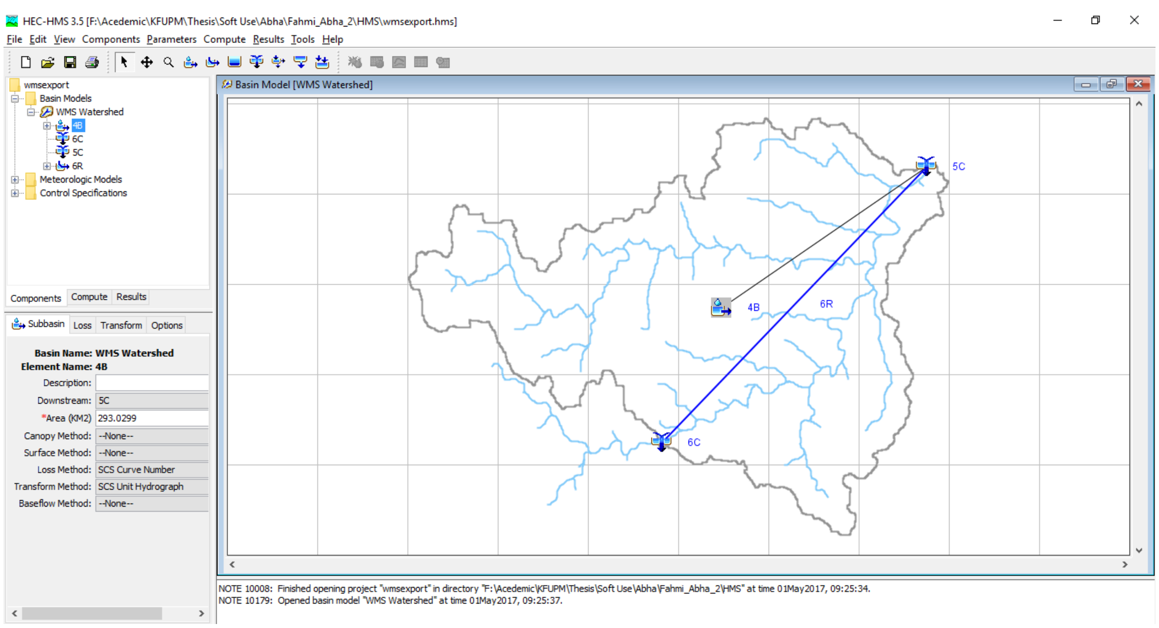


Figure 3.6: Computation of runoff for Abha in HEC-HMS

3.3.2 Rainfall Data Input

The maximum rainfall depths were considered as the most likely values. As an example, the maximum intensities for 100-year return period in Abha were 285.7, 161.6, 98.1 and 57 mm/hour for 10, 30, 60 and 120 minutes respectively (Table **3.1**). The total rainfall depths for were calculated to be 47.6 (10*285.7/60), 80.8, 98.1, and 114 mm respectively. The depth of 114 mm (for 120 minutes) was considered as the most likely value for 100-years return period. This maximum rainfall was assumed to be uniformly distributed over 24 hours (as SCS rain) due to the fact that the rainfall with short durations (1 or 2-hour) are dominant in Saudi Arabia [67]. Moreover, the hyetograph of the SCS rain has low intensity over 24 hours except for the central part where the higher intensity is dominant for 1 - 2 hours [68]. This justifies the use of 2-hour rainfall events over the 24-hour duration in the SCS method. To incorporate uncertainty, the minimum and maximum rainfall depths were obtained as: ± 20% (as standard deviation)' with the most likely values (Table **3.2**). These assumptions are somewhat arbitrary. With the availability of more data, the minimum and maximum values can be obtained and the estimations can be performed more reliably.

Table 3.2: Assumption of most likely, minimum and maximum rainfall depth (mm)

Area name	Return periods (year)	Rainfall depth (mm) (found from IDF chart)	Rainfall depth (mm/storm event) with '20%' standard deviation		
			Most likely	Minimum (- 20%)	Maximum (+ 20%)
Abha	100	114	114	91.2	136.8
	50	100.2	100.2	80.2	120.2
	25	86.2	86.2	69	103.4
Al-Baha	100	101	101	80.8	121.2
	50	88.2	88.2	70.6	105.8
	25	75.4	75.4	60.3	90.5
Bisha	100	46.4	46.4	37.1	55.7
	50	41.4	41.4	33.1	49.7
	25	36.4	36.4	29.1	43.7
Jizan	100	89.6	89.6	71.7	107.5
	50	79.6	79.6	63.7	95.5
	25	69.8	69.8	55.8	83.8
Khamis-Mushait	100	80.6	80.6	64.5	96.7
	50	71.4	71.4	57.1	85.7
	25	62	62	49.6	74.4

The rainfall depths in Table **3.2** are expected in a single storm event. To obtain the number of such storm events in each year, the yearly rainfall depths were divided by these depths. For instance, the annual average rainfall in Abha was reported to be 215 mm [17] whereas the maximum rainfall depth in a 100-years storm was 114 mm (from IDF curves). There is a possibility of an average of 1.9 (215/114) equivalent storms in Abha in a year. The average number of equivalent storms in a year are presented in Table **3.3**.

Table 3.3: Number of events in study areas for different return period

Area name	Return periods (year)	Rainfall depth per event (mm/event)	Rainfall depth per year (mm/year)	Number of event per year (Col. 4/Col.3)
Abha	100	114	215	1.9
	50	100.2	215	2.2
	25	86.2	215	2.5
Al-Baha	100	101	139	1.4
	50	88.2	139	1.6
	25	75.4	139	1.8
Bisha	100	46.4	88.7	1.9
	50	41.4	88.7	2.1
	25	36.4	88.7	2.4
Jizan	100	89.6	138	1.5
	50	79.6	138	1.7
	25	69.8	138	2
Khamis-Mushait	100	80.6	193	2.4
	50	71.4	193	2.7
	25	62	193	3.1

3.3.3 Quantifying Runoff

A total of 9 combinations were obtained for two parameters (CN and rainfall depth).

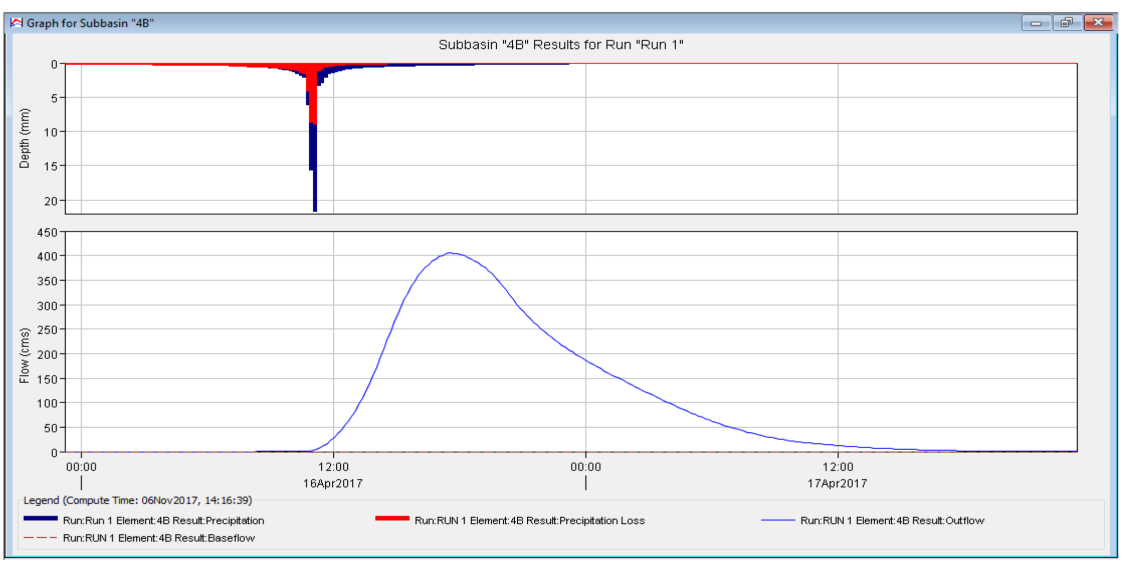


Figure 3.7: Hydrograph for 114 mm rain and CN 75 for Abha watershed

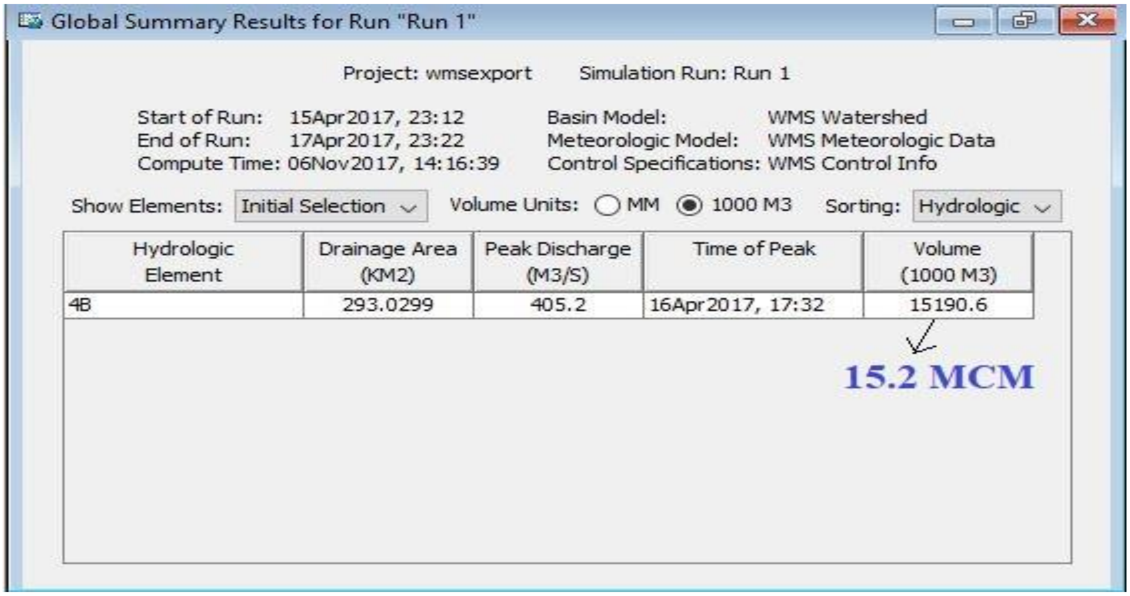


Figure 3.8: Summary for 114 mm rain and CN 75 for Abha watershed

3.3.4 Quantifying Reservoir Volume

The dimensions of the dam and the reservoir volume were computed using multiple tools. The area for the reservoirs were delineated in Google Earth, considering the land and property loss as low as possible. The free-boards were considered 4 to 5% of the dams' height [69]. The bathymetry of the delineated reservoir was converted to 'Spot Level' using TCS Converter and ArcGIS software. Later, the TIN (Triangulated Irregular Network) was developed from the 'Spot Level' using the ArcGIS software (Figure **3.9**).

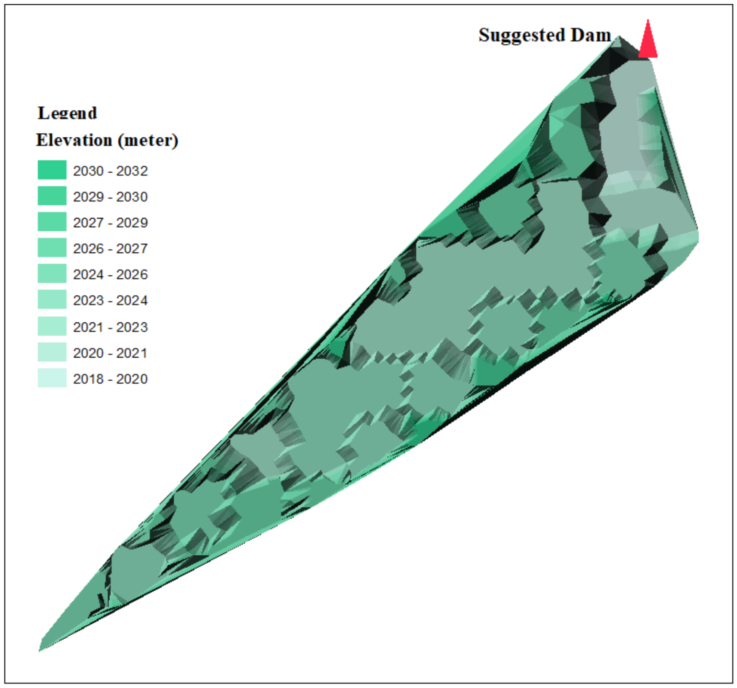


Figure 3.9: TIN image of Abha reservoir

From the TIN data, raster data was generated using the linear method in ArcGIS. The volume was calculated from the raster file using the same software.

3.4 Uncertainty Analysis

The input data and model parameters are likely to have uncertainty, which deserved further attention. In this study, uncertainty associated with rainfall depth and CN values were incorporated through incorporating their ranges. These ranges were used for input parameters and the runoff was estimated. The fuzzy set theory was used in evaluating the scenarios of rainfall-runoff relationships. The fuzzy rule-based techniques were employed. The basic information on fuzzy set theory is introduced below:

3.4.1 Fuzzy Set Theory

Fuzzy set theory transforms the inaccurate, qualitative and vague information into mathematical reasoning [70]. The advantages of this theory prevail over the other theories of uncertainty characterization while data are not adequate or imprecise and/or qualitative. In fuzzy set, an element has variable membership grade ranging between 0 and 1 while in the traditional set, the membership is either 0 or 1. The parameter values are incorporated through membership functions [57]. The membership function $\mu_a(x)$ with triangular fuzzy numbers (TFN) is presented as:

$$\mu_a(x) = \begin{cases} \dfrac{x-a}{b-a}, & a \le x \le b \\ \dfrac{x-c}{b-c}, & b \le x \le c \\ 0, & otherwise \end{cases}$$

The membership function is constructed in triangular format in Figure 3.10, where the minimum and maximum values are denoted by ‘a’ and ‘c’ and the most likely value is denoted by ‘b’.

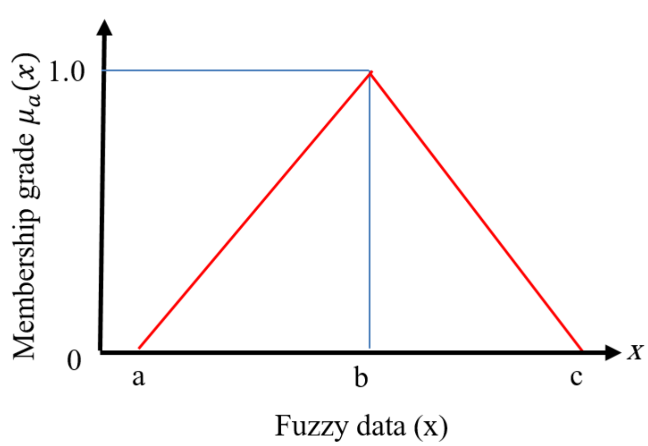


Figure 3.10: Construction of membership function

The membership function can be constructed in other forms (e.g., trapezoidal, sine, cosine, etc.). The trapezoidal and triangular fuzzy membership functions are often used to obtain the membership grades [71].

3.4.1.1Fuzzy Rule

The fuzzy rules approach with 'if-then' logic. 'If' is used for representing antecedents while, 'then' is for the consequences. Fuzzy data are aggregated through 'if-then' logic by the linguistic model as:

$Rule_i$: If a is A_i then b is B_i; $i = 1, 2, \ldots N$

Where, 'a' and 'b' are input and output variables, respectively; 'A_i' and 'B_i' are qualitatively defined function for 'a' and 'b', respectively. For multiple input parameters with single output, fuzzy rule is expressed as:

$Rule_i$: *If* a_1 *is* A_{1i} *and* a_2 *is* A_{2i} *and* a_3 *is* A_{3i} *then* b *is* B_i; $i = 1, 2, \ldots N$

The values of 'A_i' and 'B_i' are fuzzy data. These data are found after fulfilling the predefined conditions, such as poor, moderate and severe. The linguistic model is formed with '$Rule_i$' and sets of 'A' and 'B'.

As an example, Figure **3.11** depicts two input variables for predicting surface runoff (using SCS method) in Al-Baha with triangular function. The parameters are characterized by minimum, most likely and maximum values for a triangular fuzzy number [TFN] (Figure **3.11**). Ranges of rainfall depth (Figure **3.11**a) and curve number (Figure **3.11**b) were ranged from 60.3 to 90.5 mm and 62 to 92 and the most likely values were 75.4 mm and 77, respectively. The most likely values for rainfall depth and CN were assigned the membership grade of unity. A total number of $3^2 = 9$ rules were generated using all combinations of two variable input parameters (rainfall depth and CN). The fuzzy rules are shown in Table **3.4** which predicts the resulted runoff volume with a range of 2.9 – 42.9 MCM and with the most likely (average) volume of 19.1 MCM.

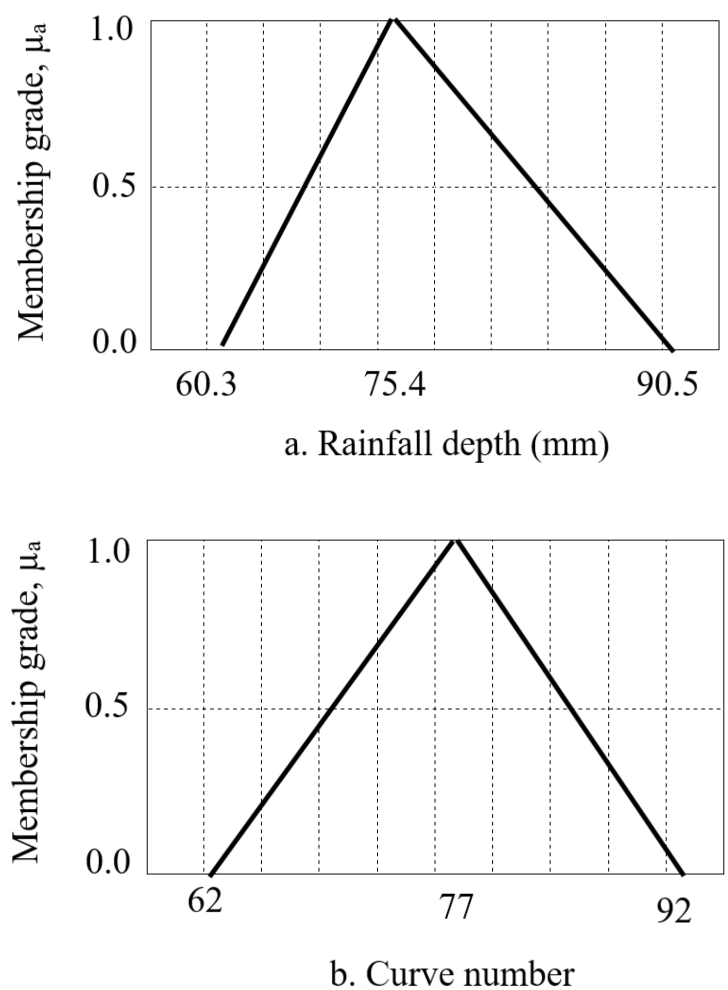


Figure 3.11: Fuzzy input variables for rainfall volume in Al-Baha (a) Rainfall depth (mm) and (b) Curve number

Table 3.4: Fuzzy rules for prediction of runoff volume in Al-Baha

Rule (R_i)	*If*	Rainfall depth	*and*	Curve number	*then*	Runoff (MCM)*
R_1	*If*	Low	*and*	Low	*then*	2.9
R_1	*If*	Medium	*and*	Low	*then*	6.1
⋮						
R_8	*If*	High	*and*	Medium	*then*	23.5
R_9	*If*	High	*and*	High	*then*	42.9

*runoff volumes were estimated using the WMS and HEC-HMS software.

3.5 Comparison of Cost Saving with Desalination Process

In Saudi Arabia, the Saline Water Conversion Corporation (SWCC) alone produces 3.4 MCM of desalinated water per day, which is 60% of the country's total desalinated water production (which results country's total daily production is 5.7 MCM) [28]. Desalinated water is costlier than the groundwater sourced supplies [72]. In this research, cost for producing desalinated water was compared with the cost of surface runoff collection and use.

The cost of desalinated water depends on several factors, including; process cost, transportation cost and maintenance cost. Three common processes (reverse osmosis (RO), Multi-effect distillation (MED) and Multi-stage flash (MSF)) are typically used for desalinating seawater in Saudi Arabia. The MSF processes are mostly used (62%), followed by the RO processes (22%) [43].

In the current research, the available data for the cost of desalinated water and runoff were obtained from past studies. However, these data could not be verified with the local conditions, which can be different from the present assessments. In past studies the overall cost of using 1 m^3 of desalinated water was found varying in the ranges of US$ 1.3 - 2.4 with the most likely value of US$ 1.8 [40].

In contrast, the cost of artificial recharge for 1 m^3 of water to ground is around US$ 0.1 [73] and the total cost of groundwater extraction and supply is approximately US$ 0.5 per 1 m^3 of water [40]. Further, the water needs transportation from the outlet location to the city. Few studies reported water transportation cost in terms of distance [74], [75]. The Economic and Social Commission for Western Asia (ESCWA) noted the following equation for estimating cost for water transportation [30].

$$\text{Transportation cost } (\$/m^3) = 0.10x + 0.09y \qquad (5)$$

where, x = horizontal transfer distance (in 100 km); y = vertical distance (in 100 m). The horizontal and vertical distances of the nearest city centres in Abha (to Abha city), Al-Baha (to Al-Aqiq city), Bisha (to Bisha city), Jizan (to Baysh city), Khamis Mushait (to Khamis Mushait city) from the outlet points were estimated to be 13, 32, 40, 16, 25 km and 175, 234, 0, 20, 110 meters respectively. Following Equation (5), water transportation cost was estimated for Abha area as: (0.1*0.13) + (0.09*1.75) = 0.2 $\$/m^3$. Similarly, water transportation cost for Al-Baha, Bisha, Jizan and Khamis Mushait area were estimated as: 0.2, 0.0, 0.0 and 0.1 $\$/m^3$.

Through considering the cost in artificial recharge (US$ 0.1), groundwater extraction (US$ 0.5) and transportation (US$ 0.2 for Abha), the total cost of surface runoff water becomes approximately US$ 0.8 (= 0.1 + 0.5 + 0.2) per m^3 of water for Abha area and 0.8, 0.7, 0.6 and 0.7 US$/$m^3$ for Al-Baha, Bisha, Jizan and Khamis Mushait area, respectively. Replacement of 1 m^3 of desalinated water by 1 m^3 of surface runoff can save US$ 0.5 (1.3- 0.8) - 1.6 (2.4 -0.8) for Abha area, depending on the cost of desalinated water. The cost saving for the study areas are presented in Table **3.5**.

Table 3.5: Cost saving for the study areas by replacing 1 m^3 desalinated water by 1 m^3 surface runoff

Dam location	Minimum (US$)	Most likely (US$)	Maximum (US$)
Abha	0.5	1.1	1.6
Al-Baha	0.5	1.0	1.5
Bisha	0.7	1.2	1.7
Jizan	0.7	1.2	1.7
Khamis Mushait	0.6	1.1	1.6

3.6 Carbon Emission from Desalination Plants

During desalination, carbon dioxide is emitted. Whenever desalination process is preceded by electricity generation (as cogeneration), a fraction of CO_2 emission is excluded from the total CO_2 in the cogeneration process. Table **3.6** shows the summary of CO_2 emissions from desalination plants.

Table 3.6: CO_2 emissions for different desalination methods (Source: [76], [30])

Desalination methods	CO_2 (kg) in producing 1 m^3 of desalinated water
MSF	20.4-25.0
MSFcogen	13.9-15.6
MED	11.8-17.6
MEDcogen	8.2-8.9
RO	3.4-6.0

Table **3.6** shows that the CO_2 release varies in the range of 3.4 – 25 kg/m^3 with the average of 15 kg/m^3 of desalinated water. The RO process emits the lowest amount of CO_2 per m^3 of water while the MSF processes emit the highest amount of CO_2 (Table **3.6**). The MSF processes represent approximately 62% of the desalination plants in Saudi Arabia while few of them are used for power cogeneration [77]. This indicates that these plants are likely to emit the CO_2 in the higher ranges of Table **3.6** (e.g., 13.9 – 25 kg CO_2/m^3 of desalinated water). The surface runoff can be used to substitute desalinated water, which can lower CO_2 emissions into the environment. Benefits of using the surface runoff was predicted in this study in context to the reduction of CO_2 emission.

CHAPTER 4

DATA GENERATION

4.1 Locating New Dam Locations

With the purpose of runoff collection for domestic use five locations were selected for the new dams in five areas based on physical assessment in terms of local conditions (using the Google Earth Pro and WMS software) and geological conditions of the soil (using geological maps). Before selecting a site for new dam, the following criteria were considered:

- The sites with faults along the streams must be eliminated from potential list [78].
- Solid rock foundations are preferable, but soils with coarse sands and gravels will be satisfactory for dam with maximum 15 m height [69].
- Steep valley slopes should be given low priority as the dam on such slopes are rarely economical [79]. A narrow position over the wadi should be chosen to reduce the cross section of the dam [78], [79].
- A site where, residential areas are close to the dam in the downstream will be avoided to avoid the risk of damage by overflowing of runoff.
- The site of dam should not be far from villages. The proximity to villages can be considered as an easiness index to find the necessary skilled manpower and to minimize the cost for construction [80]. According to a past study, a threshold

value of 15 km was chosen as the distance between the dam site and the villages [78].

- To select the dam site, it is important to consider the distance from the existing road networks to minimize transportation cost of construction materials [81]. A threshold value of 15 km was also chosen [78].

4.1.1 Dam Location in Abha

Abha is situated in the east of As-Sawdah Mountain. The area is mountainous with high elevation from mean sea level. In the southwest corner of Abha city, there are two dams, named; Abha dam and Al-Meqdah (As-Saodah) dam with capacity of 2.1 MCM and 0.1 MCM respectively; and in the east, there is the Wadi Ottod dam with capacity of 6.4 MCM [9]. During heavy rain, water runs from southwestern hills to the northeast direction through the Abha city, where the elevation is relatively low. For this study, a new dam location was selected in the northeast site from the Abha city on Wadi Abha. In the selected location, there is schist, which is a type of metamorphic rock (Figure C.**1**). There is no faults or folds in the rock but exists inclined foliation in downstream from the location. Elevation of this point is 2024 m, which is more than 200 meters lower than Abha Dam. Within 5 kilometers in the downstream, there is no residential area, which would be safer to avoid the risk from overflow. Dam site is depicted in Figure **4.1**.

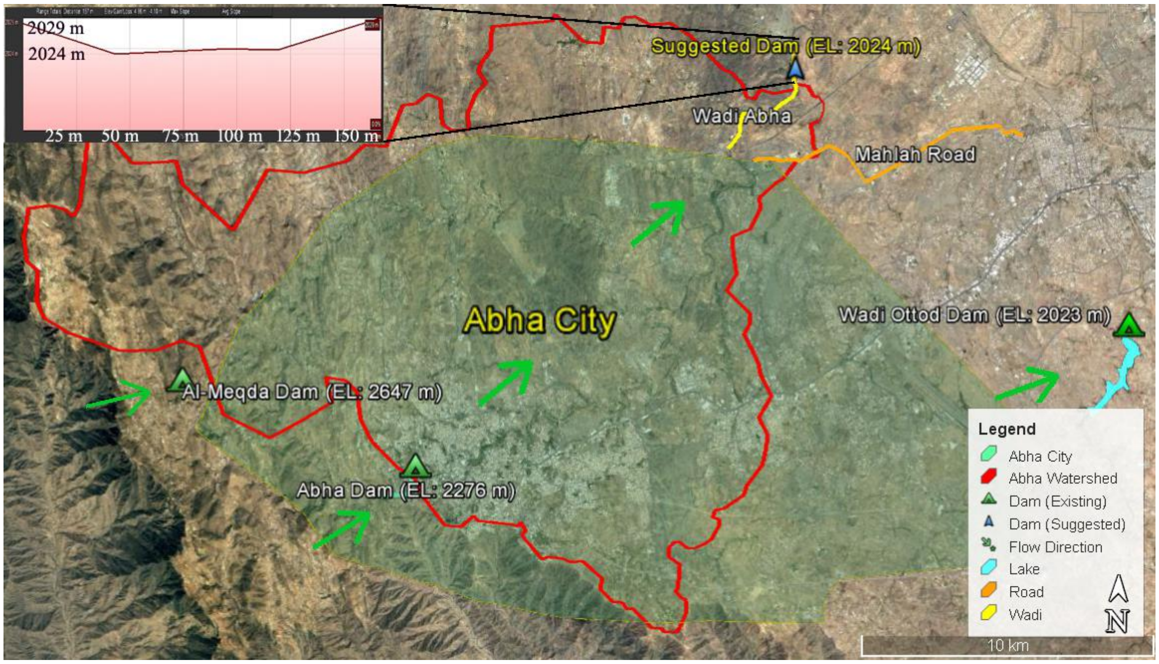


Figure 4.1: Suggested dam location with watershed (red colored) in Abha

4.1.2 Dam Location in Al-Baha

There are more than thirty dams in Al-Baha with overall capacity of 40 MCM or more [5]. Among them, Al-Aqiq dam is the largest with capacity of 19.1 MCM [9]. A new dam site was selected on Wadi Tharad, which is close to Gaabah area and towards the northern-east direction from the Al-Baha city (Figure **4.2**). The bed of wadi Tharad consists of alluvium soil. Beneath the soil, there is metavolcanic rock, which is a type of metamorphic rock (Figure C.**2**). As there is a chance of having vertical foliation in the rock, the location can be shifted by few meters ahead or behind. Elevation of this site is 1336 meter. Wadi Al-Aqiq Dam and Wadi Tharad Dam (capacity: 14.1 MCM) are on the opposite end of the suggested dam's watershed, whose elevations are more than 300 meters higher than the new dam site. Naturally, a good portion of runoff will be flowing towards the suggested dam.

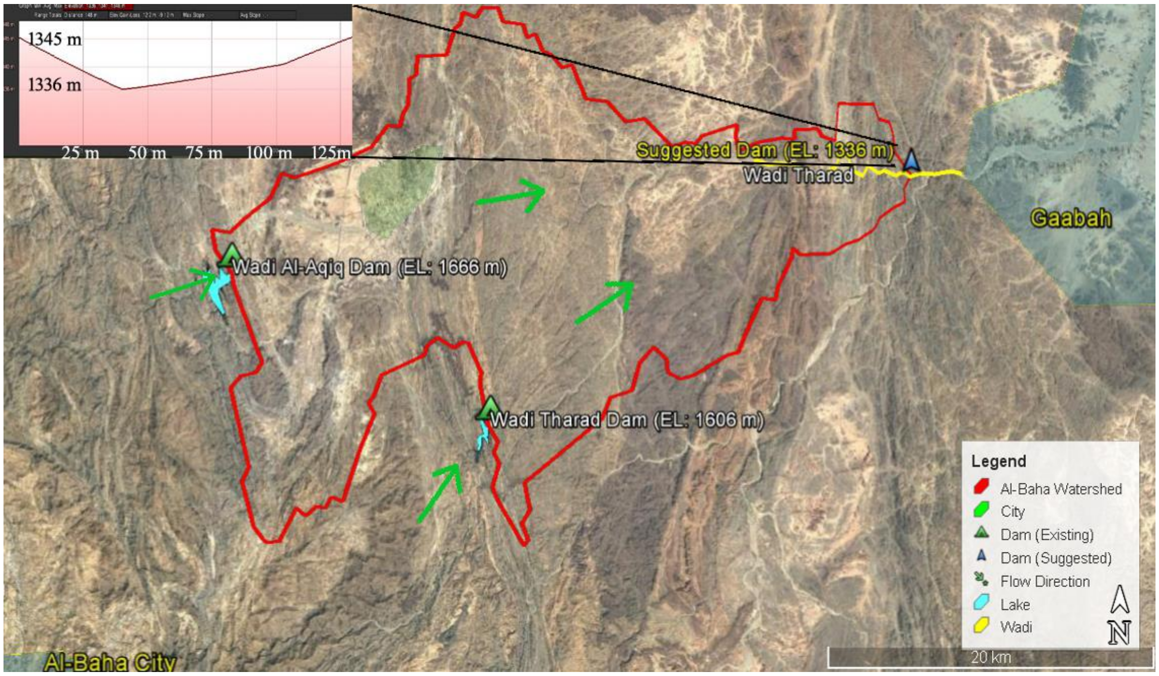


Figure 4.2: Suggested dam location with watershed (red colored) in Al-Baha

4.1.3 Dam Location in Bisha

The largest dam in Saudi Arabia, named the King Fahad Dam is situated in Bisha, whose storage capacity is 325 MCM [9]. A new dam location with is suggested on a tributary of Wadi Tarj, which is close to Al-Gafrat area and in the southwest of Bisha City (Figure **4.3**). The new dam is in the Tabalah Basin. The foundation of the dam location is of diorite, which is a type of igneous rock (Figure C.**3**). Because of the stable nature of the foundation, a large dam can be constructed here. The elevation of the new location is 1276 meter. The runoff will be coming from west to east direction in the expected watershed.

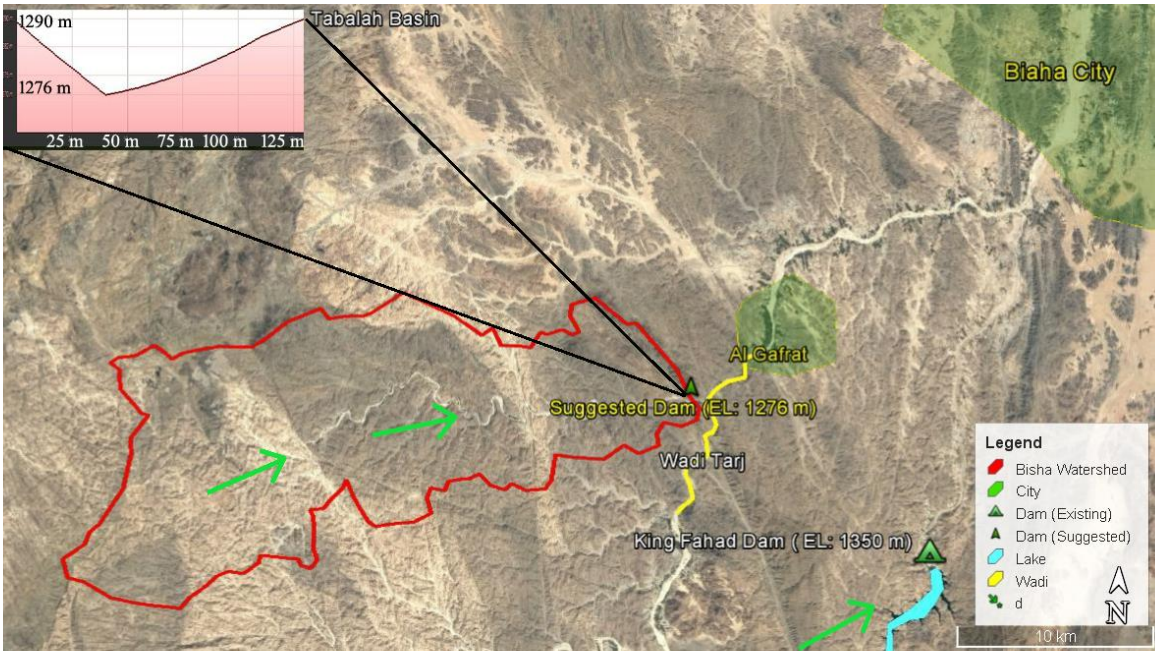


Figure 4.3: Suggested dam location with watershed (red colored) in Bisha

4.1.4 Dam Location in Jizan

The suggested dam location in Jizan is on a tributary of Wadi Baysh. The foundation of the dam location is of inactive deposits of gravel, sand and silt (Figure C.**4**). Low concrete gravity dam with height of maximum 15 m is suggested here [69]. The location is inside of Baysh Basin with an elevation of 63 meter. Wadi Qura Dam (0.6 MCM) and Wadi Wa'al Dam (2.41 MCM) are in the upstream of Um Saad area where the suggested dam site is situated (Figure **4.4**). A vertical distance of more than 200 meters exists between the two end points of the potential watershed. Another two prominent dams in Jizan are Wadi Baysh Dam and Wadi Jizan Dam, with capacity of 193.6 MCM and 51 MCM respectively, situated in the North end of Jizan and South of the suggested dam, respectively. Overall seven dams in Jizan have the capacity of storing 245 MCM or more water [5].

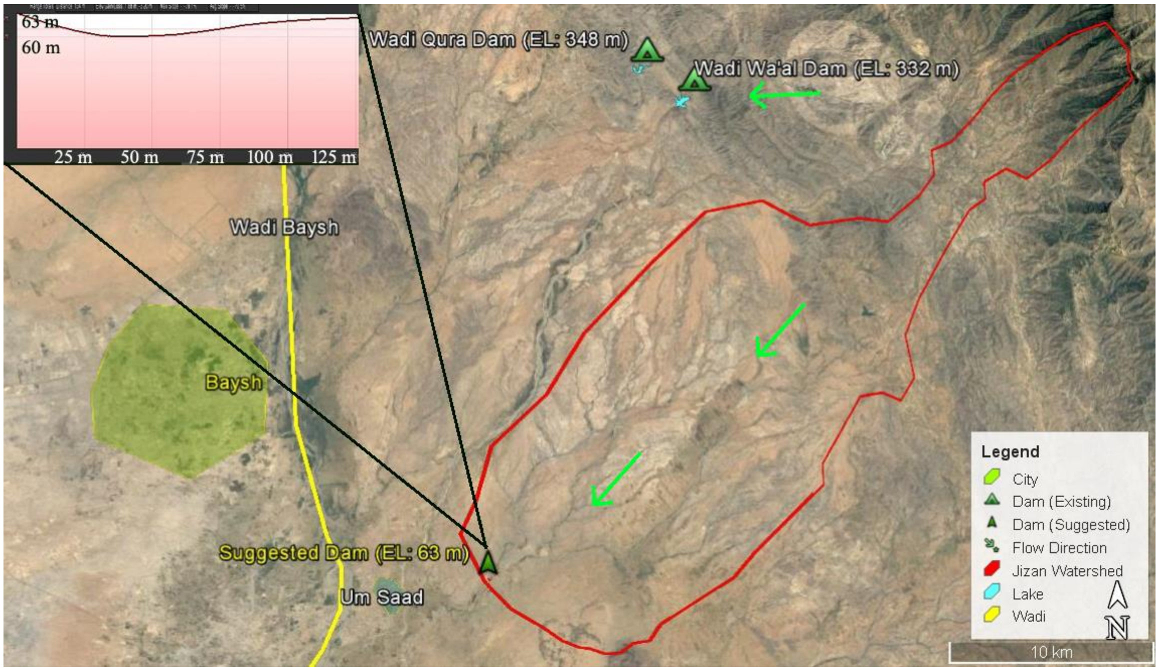


Figure 4.4: Suggested dam location with watershed (red colored) in Jizan

4.1.5 Dam Location in Khamis-Mushait

The suggested dam in Khamis-Mushait is in the Tendahah Basin on Wadi Tendahah (Figure **4.5**). The foundation of the dam location is of biotite granodiorite, which is an intrusive igneous rock similar to granite (Figure C.**5**). As the rock is free from fault, fold and foliation, the location is considered to be safe for dam construction. In the South, Khamis-Mushait City and Tendahah Dam (4.2 MCM) are located [9]. Inside the watershed, runoff would be flowing from Tendahah Dam end to the new dam end due to the vertical gap (> 50 meter)

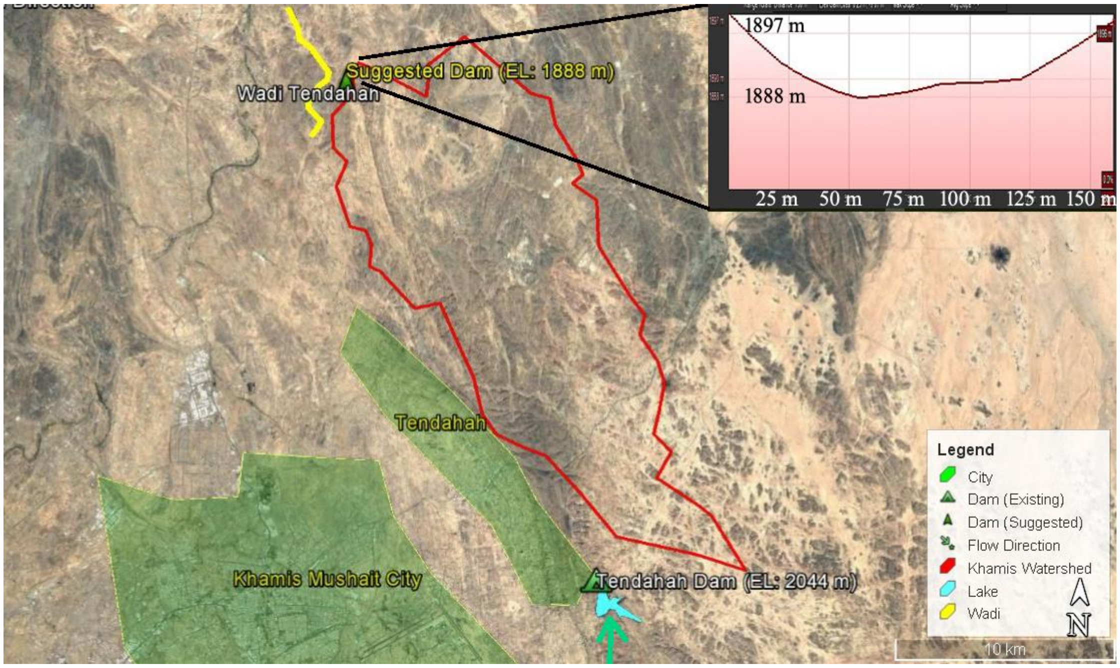


Figure 4.5: Suggested dam location with watershed (red colored) in Khamis Mushait

The selected coordinates for the new dam locations are preserved (Table **4.1**) for later use in WMS software to select the outlet points for the catchment areas.

Table 4.1: Coordinates for the suggested dam locations

Name of areas	Latitude	Longitude
Abha	18°20'7.59"N	42°36'26.13"E
Al-Baha	20°17'5.13"N	41°58'11.66"E
Bisha	19°46'12.12"N	42°22'10.10"E
Jizan	17°17'21.77"N	42°39'19.59"E
Khamis Mushait	18°30'44.78"N	42°45'49.18"E

4.2 Computation

4.2.1 Computing Flow Data and Delineating Basin

Flow direction was computed and the thalweg was accumulated using the Digital Elevation Model (DEM) data in WMS software. Thalweg is the connecting line of the deepest points over a river or a valley [82]. This thalweg in valley acts as stream during rainfall. After that, an outlet point was placed on the accumulated streamlines generated in WMS using the preserved coordinate (Figure **4.6**).

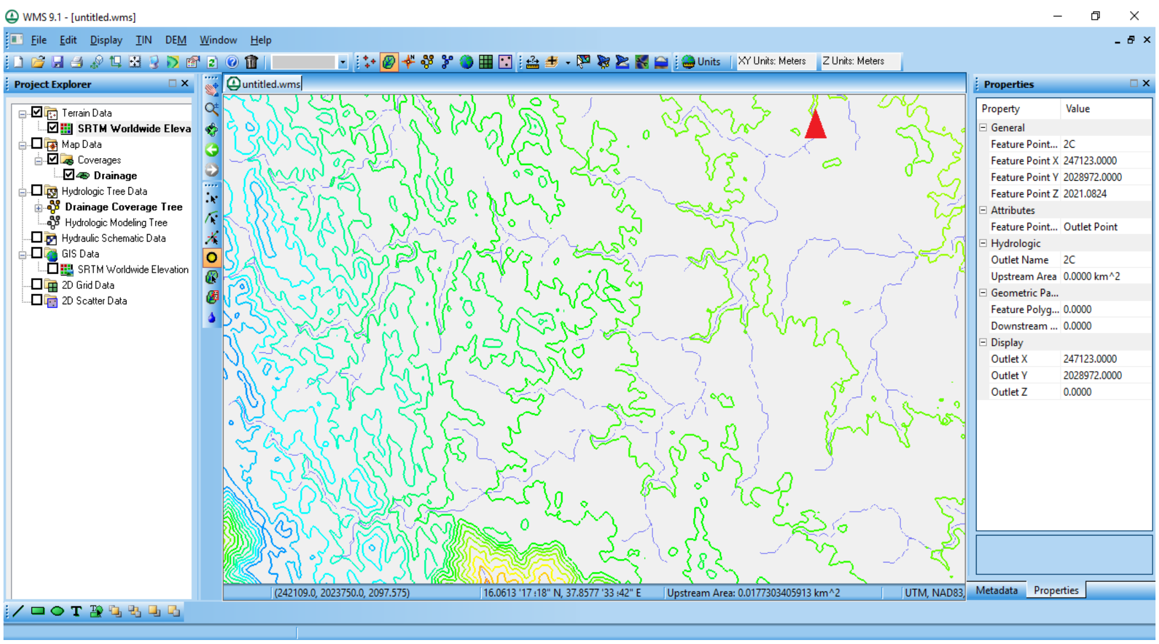


Figure 4.6: Outlet Point over the stream line for the Abha area (red colored)

The selected outlet point was checked whether it was upon the wadies or not. Wadi lines for Saudi Arabia were available as KMZ file (Google Earth File). Figure **4.7** shows that the selected point was placed upon the wadi lines (black colored circle) (Figure **4.7**).

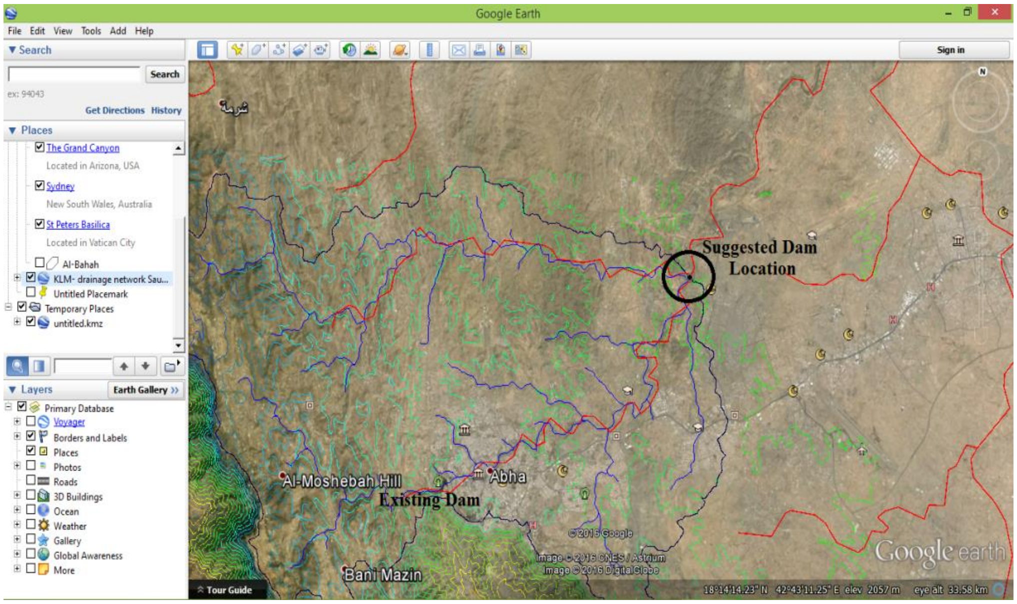


Figure 4.7: Checking suitability of dam locations with wadi lines

To get a separate watershed from the existing dams, outlet points were placed on the positions of suggested and existing dams in WMS window. WMS software delineates the sub-basins separately. Figure **4.8** is the delineated watershed for the suggested dam location in Abha, where the white colored area is the watershed of existing Abha Dam. In this way five watersheds were delineated for five study areas. The areas of delineated watersheds are presented in Table **4.2**.

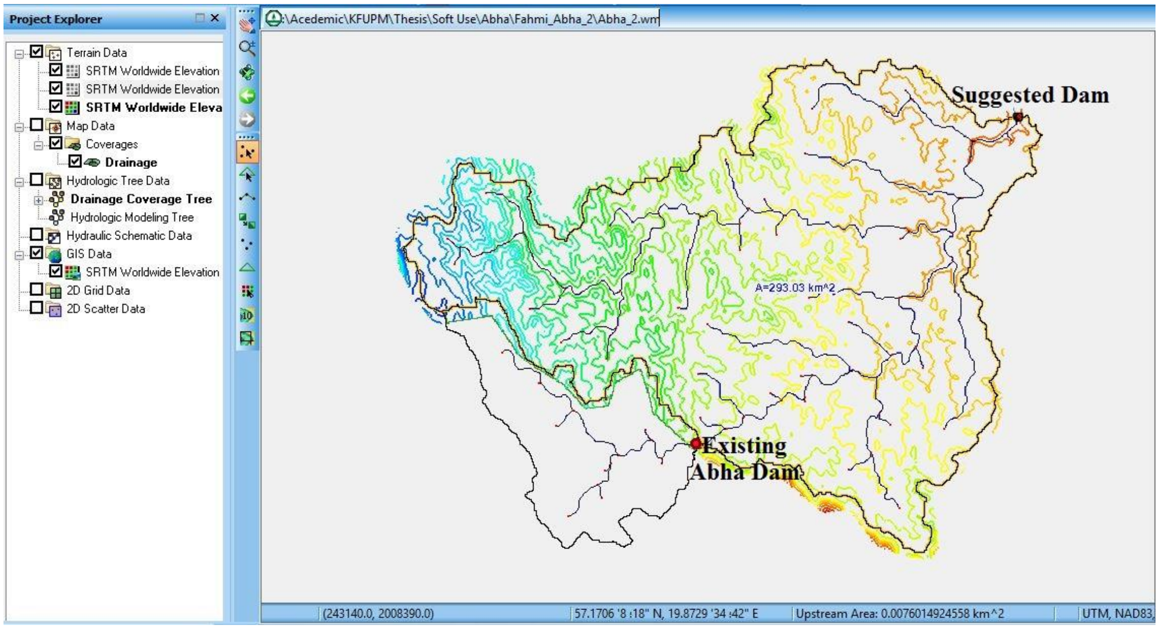


Figure 4.8: Delineated catchment area for corresponding outlet point (in Abha area)

Table 4.2: Areas of delineated watersheds

Name of watershed	Area of watershed
Abha	293 km^2
Al-Baha	626.3 km^2
Bisha	270.8 km^2
Jizan	329.1 km^2
Khamis Mushait	183.2 km^2

4.2.2 Computing Curve Number

The Curve Number (CN) were computed in different ways depending on data availability.

4.2.2.1CN for Abha

Abha is a mountainous but urbanized area. Volcanoclastic, shale and siltstone are prevailing as different types of rocks in the mountains. The dominated soil types are loam, loamy sand and sandy clay loam [83]. A soil map for the new watershed was digitized (Figure **4.9**) using the Geographic Information System (GIS) software based on the soil texture map for Abha watershed as developed by Mallick (2016).

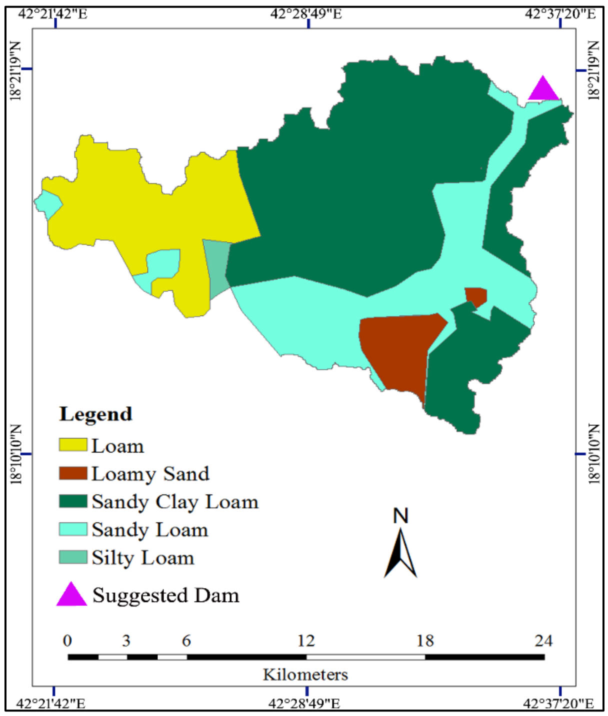


Figure 4.9: Soil type of Abha watershed [83]

The soil types were classified per Hydrologic Soil Group (HSG) as; A, B and C (Figure **4.10**).

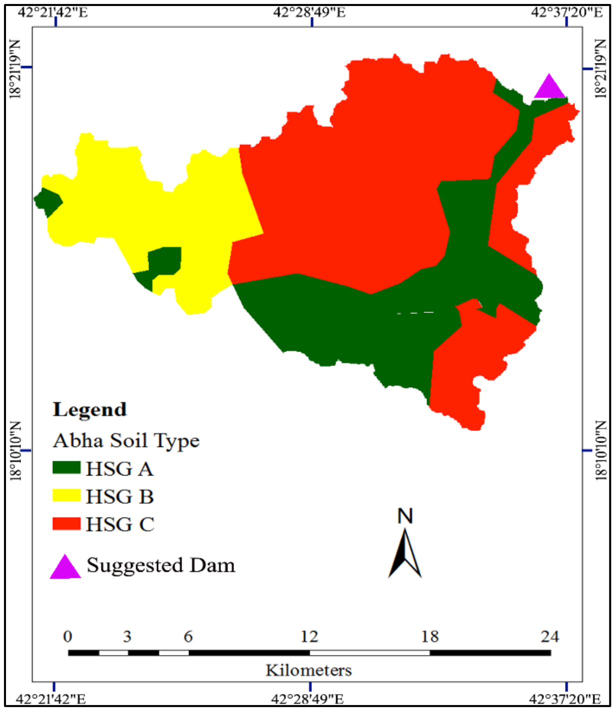


Figure 4.10: Hydrologic soil group for Abha watershed

Land use and land cover (LULC) data were downloaded as Shape File from Aquaveo's website named 'wLandUse_bl224.shp' which covers partial parts of study areas [62]. The remaining parts were digitized manually based the Base Map (Imagery) of Abha watershed in GIS software (Figure **4.11**).

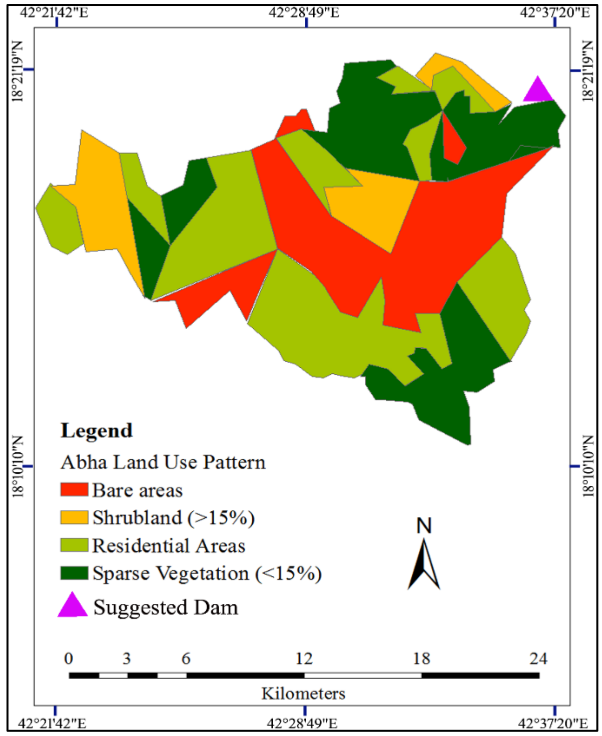


Figure 4.11: Land use pattern in Abha watershed

Using GIS software, the combination of Soil Type map and Land Use Pattern map developed a new map (Figure **4.12**). The Attribute Table of this file was saved in Excel file for CN computation.

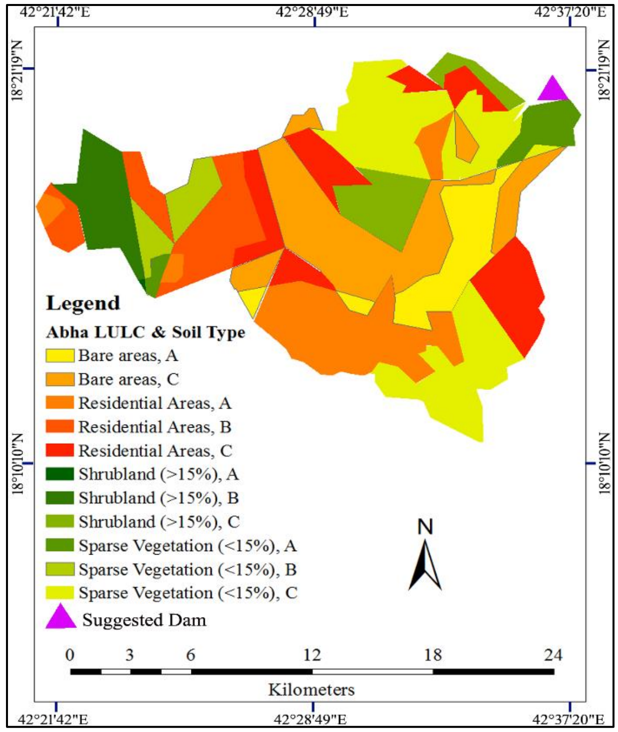


Figure 4.12: Land use and soil type pattern in Abha watershed

For HSG A, B and C the CN values were assumed as: 77, 86 and 91 for bare areas; 57, 72 and 81 for residential areas (assuming 30% average impervious area); 49, 69 and 79 for shrub-land and 63, 77 and 85 for sparse vegetation, respectively [84], (Table **4.3**).

Table 4.3: Calculating the composite curve number (CN) for Abha watershed

LULC.	HSG	Area, Ai (km^2)	CN_i value	A_i*CN_i
Bare areas	A	28.5	77	2195.3
Bare areas	C	48.4	91	4406.8
Residential Areas	A	38	57	2168.4
Residential Areas	B	5.1	72	367.4
Residential Areas	C	58.1	81	4709.1
Shrubland (>15%)	A	16.4	49	802.3
Shrubland (>15%)	B	0.2	69	11.6
Shrubland (>15%)	C	16.7	79	1320.5
Sparse Vegetation (<15%)	A	35.9	63	2260.7
Sparse Vegetation (<15%)	B	15.5	77	1194.4
Sparse Vegetation (<15%)	C	28.6	85	2429.6
$\sum$		291.5		21866.1

Using these CN values, the composite CN for Abha was calculated following the Equation (2) as:

$$\mathrm{CN}_{\mathrm{composite}} = \frac{21866.1}{291.5} = 75$$

Thus, composite CN for Abha watershed is 75.

4.2.2.2CN for Al-Baha

Al-Baha is very high from mean sea level with various types of geography, including plain lands, mountains, valleys and green lands. Al-Baha is dominated by loamy soil [85]. The watershed map for the suggested dam was superimposed on the Soil Type map and LULC map, developed by Mahmoud et al. (2014) [85]. From the superimposed map the soil type for the current watershed has been defined as HSG B (Loamy soil) (Figure **4.13**). The land use pattern map for the current watershed has been extracted from the LULC map (Figure **4.14**), using GIS.

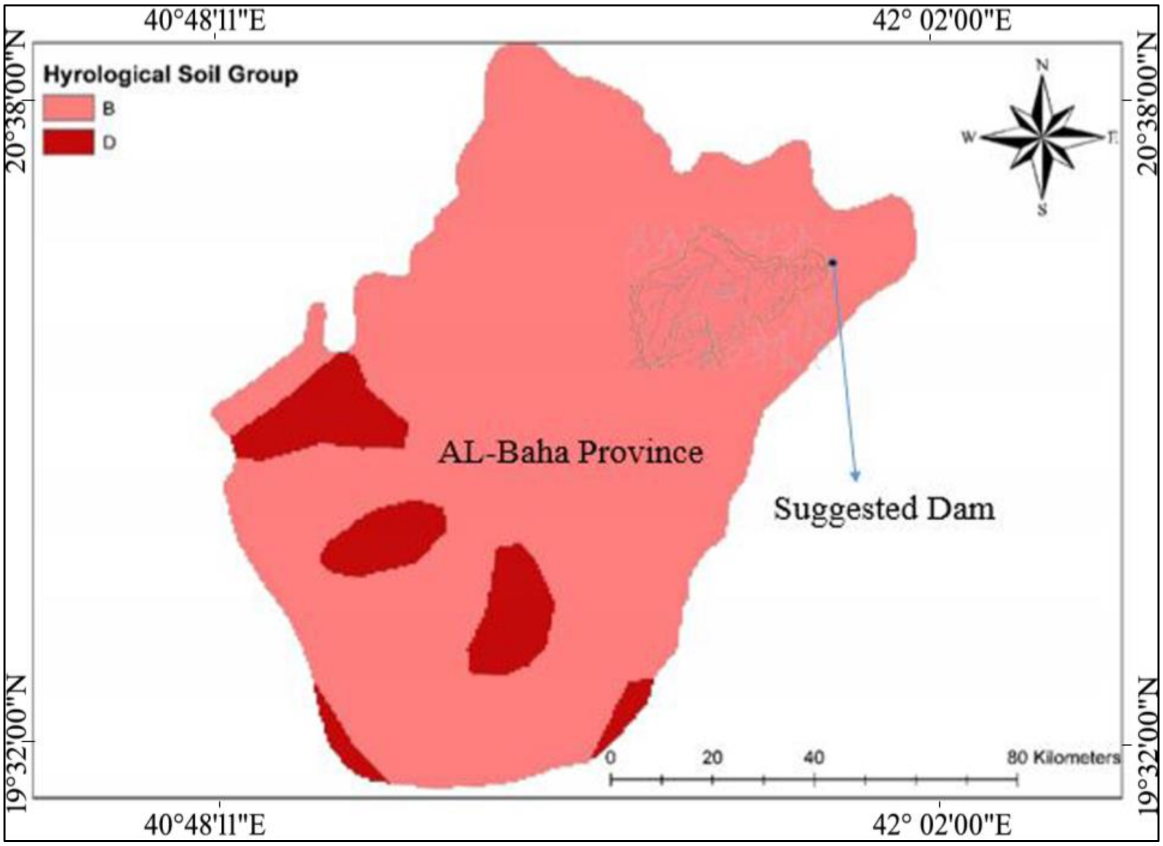


Figure 4.13: Hydrologic soil group of Al-Baha watershed [85]

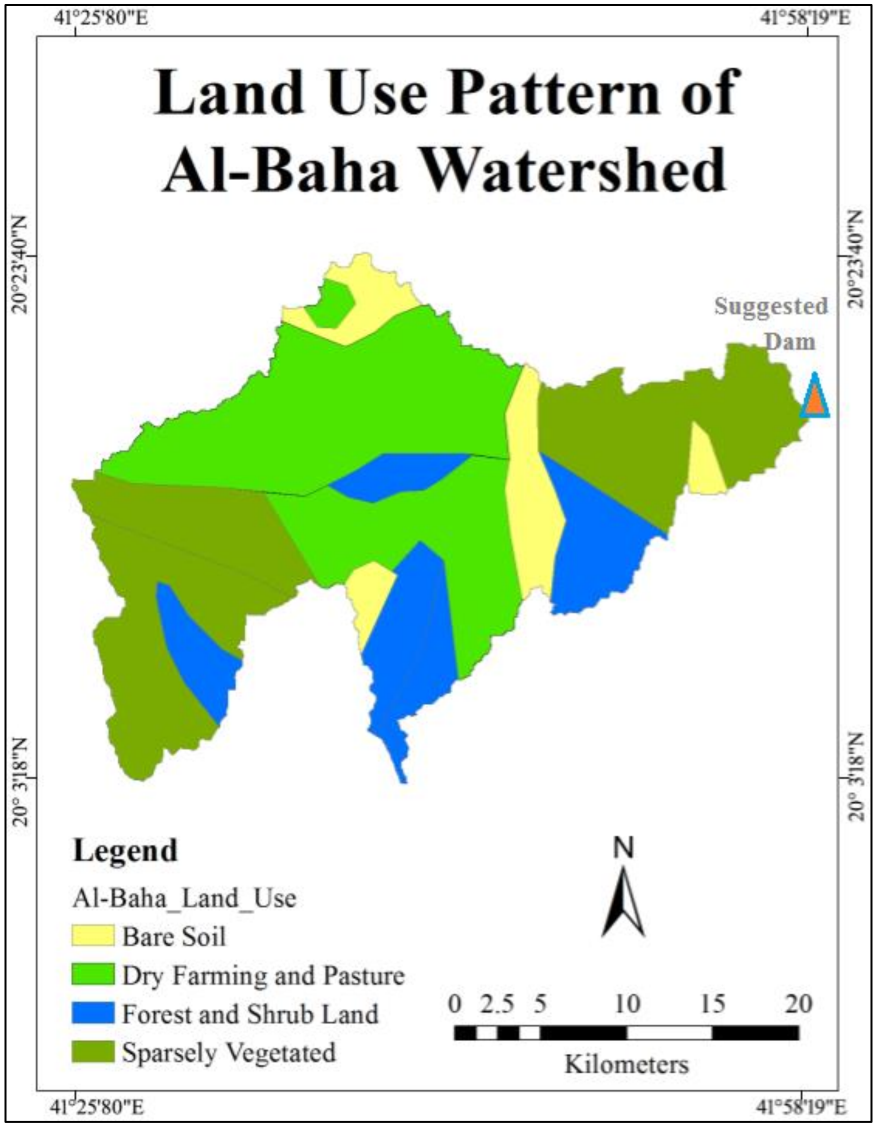


Figure 4.14: Land use pattern of Al-Baha watershed [85]

For HSG B, the CN values were assumed as: 86 for bare soil, 79 for dry farming and pasture, 69 for forest and shrub land and 77 for sparsely vegetated area [84], (Table **4.4**).

Table 4.4: Calculating the composite curve number (CN) for Al-Baha watershed

LULC.	HSG	Area, Ai (km^2)	CN_i value	A_i*CN_i
Bare Soil	B	61.2	86	5263.1
Dry Farming and Pasture	B	236.8	79	18708.9
Forest and Shrub Land	B	107.9	69	7444
Sparsely Vegetated	B	220.4	77	16968.4
$\sum$		626.3		48384.3

Using these CN values, the composite CN for Al-Baha was calculated following the Equation (2) as:

$$\mathrm{CN}_{\mathrm{composite}} = \frac{48384.3}{626.3} = 77.3$$

Thus, composite CN for Al-Baha watershed is 77.3.

4.2.2.3 CN for Bisha

The watershed for the suggested dam in Bisha is inside of the Tabalah basin. The Curve Number for Tabalah basin was noted as 73.4 [86]. In this study, the same CN was used.

4.2.2.4 CN for Jizan

The watershed for the suggested dam in Jizan is inside of the Baysh basin. The Curve Number for Baysh basin was reported to be 72.2 [86]. In this study, the same CN is used.

4.2.2.5 CN for Khamis-Mushait

The soil type of Khamis-Mushait is dominated by loamy sand and loam [87]. Soil type and LULC map for Asir province were developed by Mahammad and Adamowski (2015)

[87]. Superimposition of the map of Khamis-Mushait watershed with the Asir Soil Type map shows the soil type of Khamis-Mushait watershed. The soil type was characterized as the HSG A category (Figure **4.15**). Superimposition with LULC map shows that approximately two-thirds of the watershed is in Barren or Sparsely Vegetated land and the other one-third is in Mixed Shrubland/Grassland (Figure **4.16**).

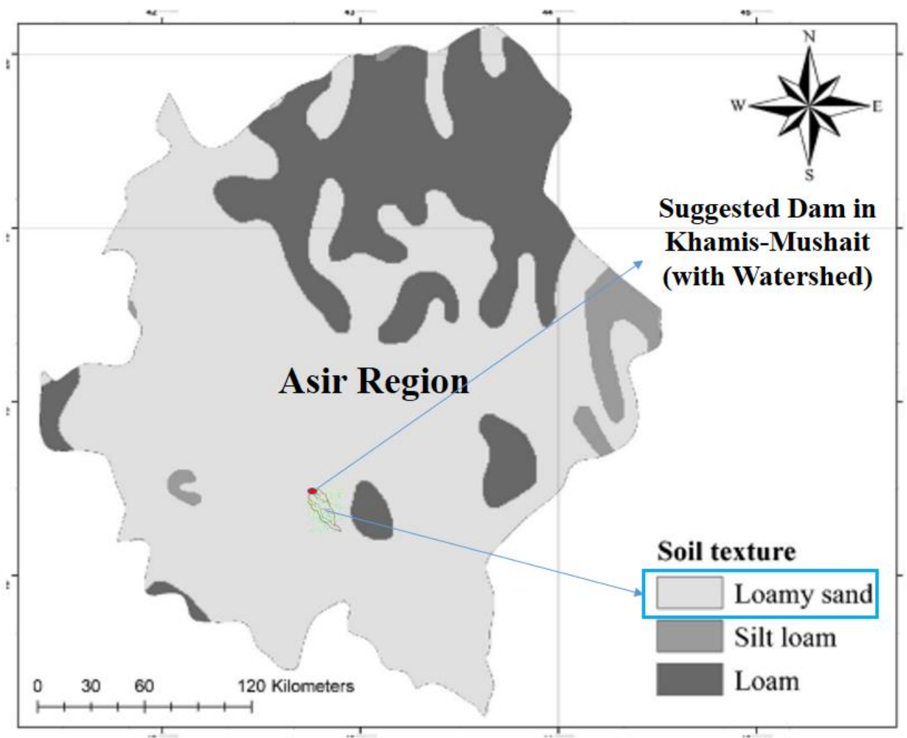


Figure 4.15: Hydrologic soil group of Khamis-Mushait watershed [87]

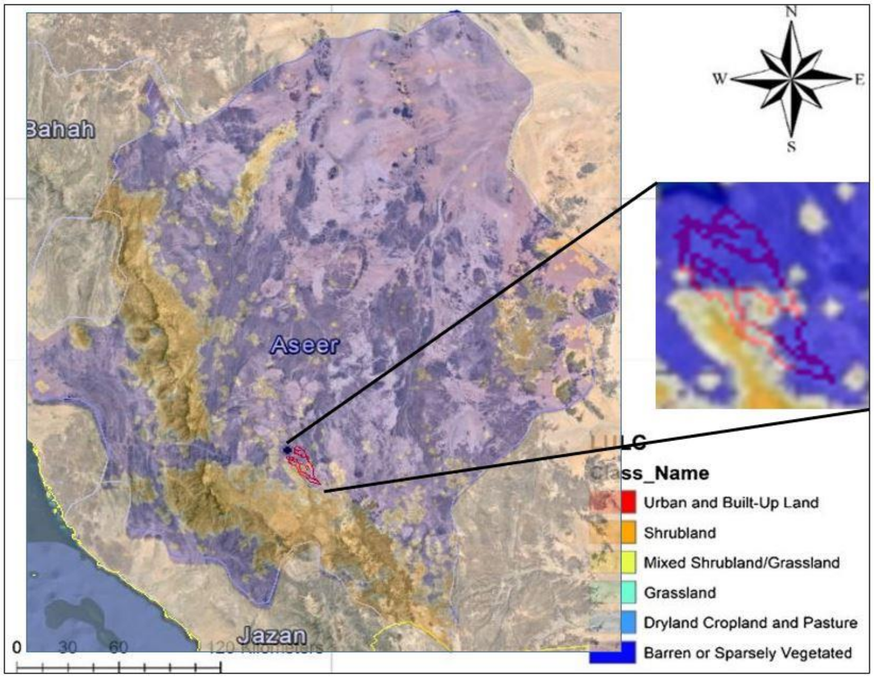


Figure 4.16: Land use pattern of Khamis-Mushait Watershed [87]

For HSG A soil, CN were assumed 77 for Barren or Sparsely Vegetated land and 49 for Mixed Shrubland or Grassland [84], (Table **4.5**).

Table 4.5: Calculating the composite curve number (CN) for Khamis-Mushait watershed

LULC.	HSG	Area, Ai (%)	CN_i value	A_i*CN_i
Barren or Sparsely Vegetated Land	A	67	77	5159
Mixed Shurbland or Grassland	A	33	49	1617
$\sum$		100		6776

Using these CN values, the composite CN for Khamis-Mushait was calculated following the Equation (2) as:

$$CN_{composite} = \frac{6776}{100} = 67.8$$

The composite CN became 67.76 for Khamis-Mushiat watershed

To incorporate uncertainty in CN values, the rounded values of CN were assumed as the most likely CN with a standard deviation of 15 for the minimum and maximum CN. The minimum, most likely and maximum values of CN were obtained for Al-Baha, Bisha, Jizan and Khamis Mushait and are presented in Table **4.6**.

Table 4.6: Assumption of most likely, minimum and maximum values for CN

Area name	Area (km^2)	CN from computation	CN with '15' standard deviation		
			Assumed most likely CN	Minimum CN (-15)	Maximum CN (+15)
Abha	293.0	75	75	60	90
Al-Baha	626.3	77.3	77	62	92
Bisha	270.8	73.4	73	58	88
Jizan	329.1	72.2	72	57	87
Khamis	183.2	67.8	68	53	83

4.2.3 Computing Reservoir Volume

For each outlet of the five watersheds, dimensions of the dams and the reservoir volumes were computed using the methodology noted in Section 3.3.4. The details of the dams and reservoirs are presented in Table **4.7**.

Table 4.7: Dimensions of dams and area and volume of reservoirs

Area name	Dam width	Dam height	Reservoir area	Reservoir volume
Abha	150 m	5 m	0.2 km^2	1.3 MCM
Al-Baha	125 m	9 m	0.5 km^2	4.7 MCM
Bisha	125 m	14 m	1.5 km^2	23.8 MCM
Jizan	110 m	3 m	0.4 km^2	0.8 MCM
Khamis Mushait	150 m	9 m	0.6 km^2	4.6 MCM

CHAPTER 5

RESULTS AND DISCUSSION

5.1 Results

5.1.1 Abha

For 25-year return period and the low rainfall event (69 mm), the runoff per event was estimated in the range of 1.8 – 12.8 MCM, with an average of 6.8 MCM. For the most likely rainfall event (86.2 mm), this range was 3.6 – 17.5 MCM, with an average of 10.1 MCM. For the high rainfall (103.44 mm), the runoff was estimated in the range of 5.9 – 22.2 MCM, with an average of 13.7 MCM (Figure **5.1**).

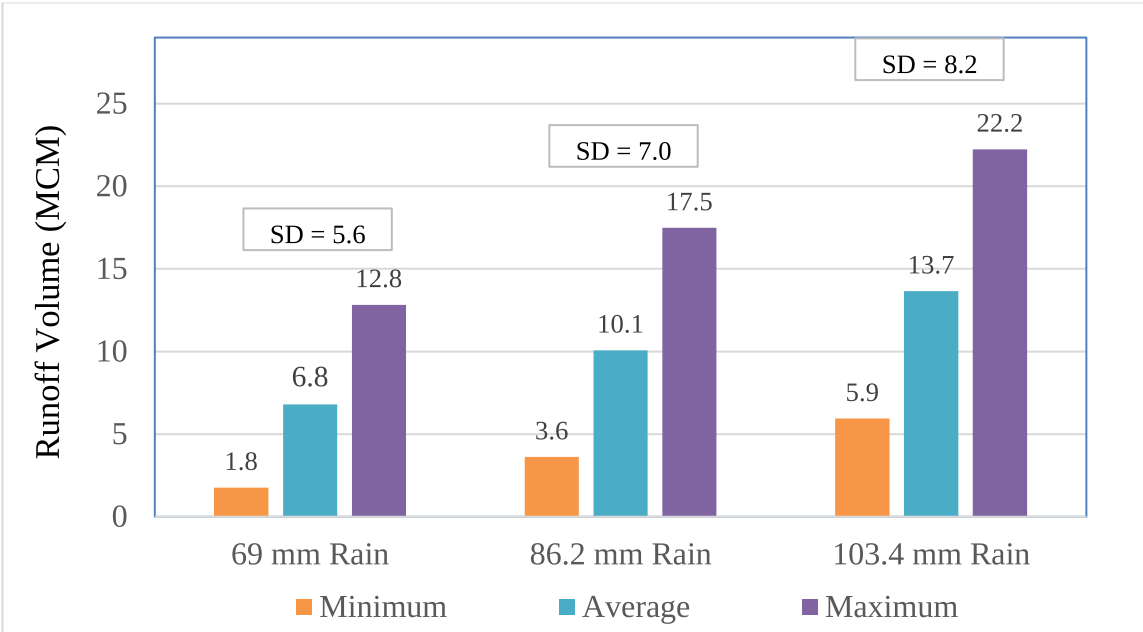


Figure 5.1: Variation of runoff volume with standard deviation (SD) for different rainfall depths in Abha basin (Runoff are estimated for a single event of rainfall, for 25-year return period)

For the CN values of 60, 75 and 90, average runoff volumes per event were 3.8, 9.3 and 17.5 MCM and their corresponding ranges were 1.8 – 5.9, 5.8 – 12.8 and 12.8 – 22.2 MCM respectively (Figure 5.2).

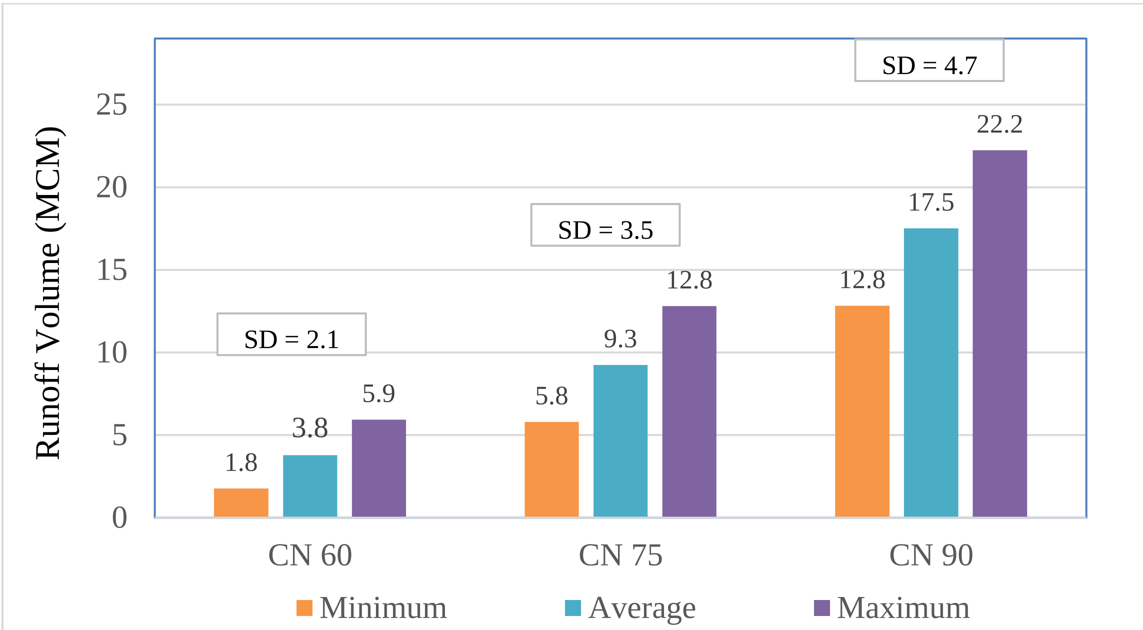


Figure 5.2: Variation of runoff volume with standard deviation (SD) for different curve numbers in Abha basin (Runoff are estimated for a single event of rainfall, for 25-year return period)

For 50-year return period and the low rainfall event (80.2 mm), the runoff per event was estimated in the range of 2.9 – 15.8 MCM, with an average of 8.9 MCM. For the most likely rainfall event (100.2 mm), this range was 5.5 – 21.3 MCM, with an average of 13.0 MCM. For the high rainfall (120.2 mm), the runoff was estimated in the range of 8.6 – 26.9 MCM, with an average of 17.4 MCM (Figure **5.3**).

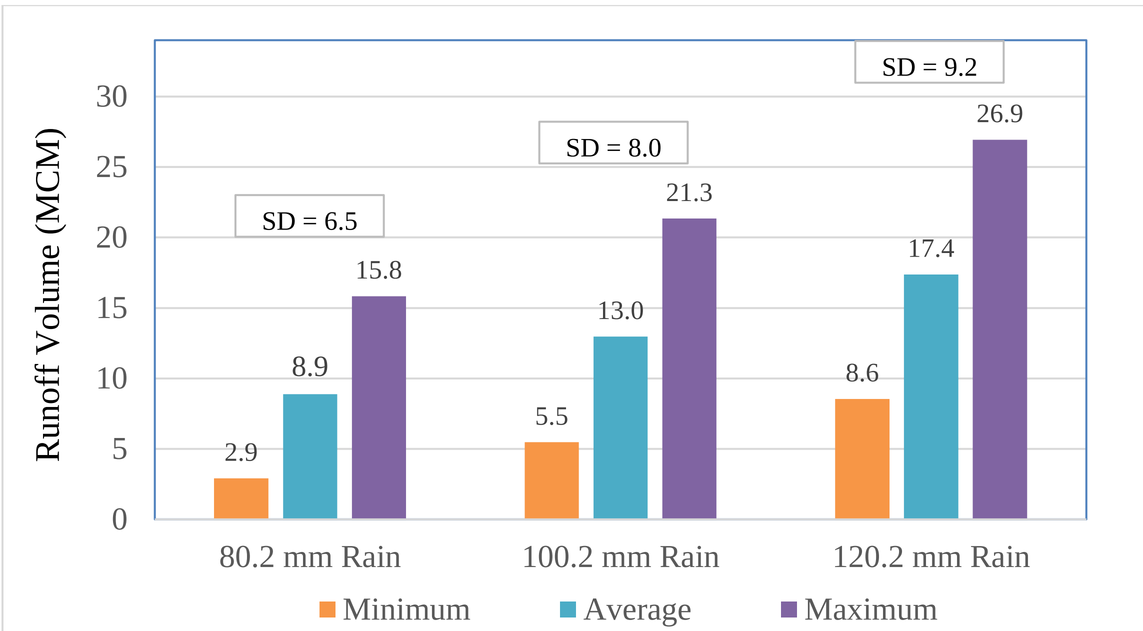


Figure 5.3: Variation of runoff volume with standard deviation (SD) for different rainfall depths in Abha basin (Runoff are estimated for a single event of rainfall, for 50-year return period)

For the CN values of 60, 75 and 90, average runoff volumes per event were 5.6, 12.1 and 21.4 MCM and their corresponding ranges were 2.9 – 8.6, 7.9 – 16.6 and 15.8 – 26.9 MCM respectively (Figure **5.4**).

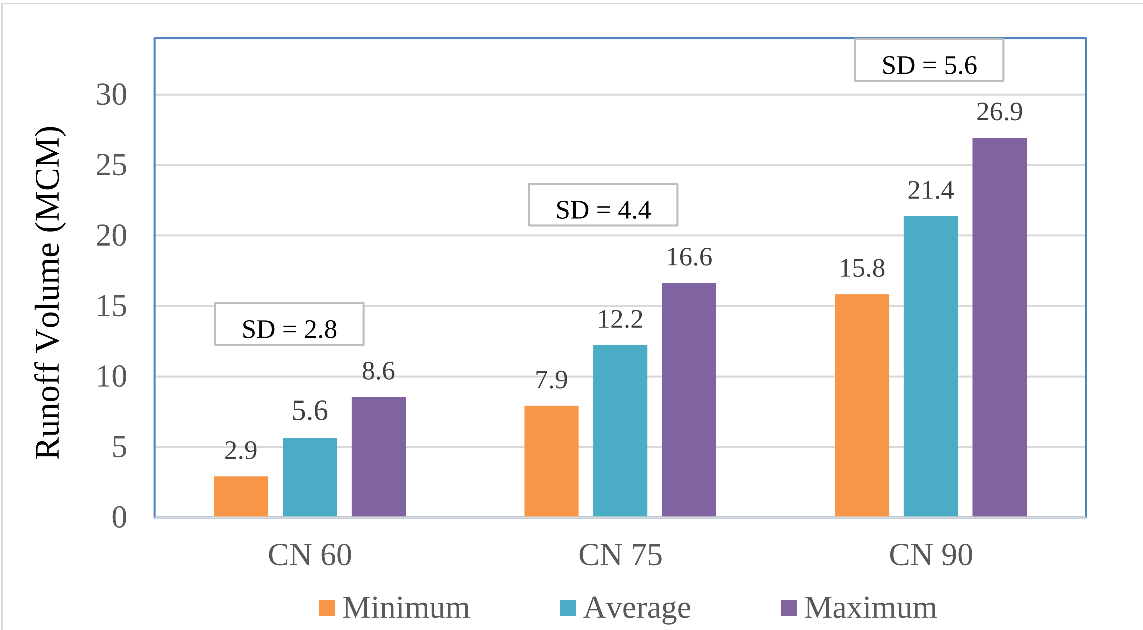


Figure 5.4: Variation of runoff volume with standard deviation (SD) for different curve numbers in Abha basin (Runoff are estimated for a single event of rainfall, for 50-year return period)

For 100-year return period and the low rainfall event (91.2 mm), the runoff per event was estimated in the range of 4.3 – 18.9 MCM, with an average of 11.1 MCM. For the most likely rainfall event (114 mm), this range was 7.5 – 25.2 MCM, with an average of 16.0 MCM. For the high rainfall (136.8 mm), the runoff was estimated in the range of 11.4 – 31.6 MCM, with an average of 21.2 MCM (Figure **5.5**).

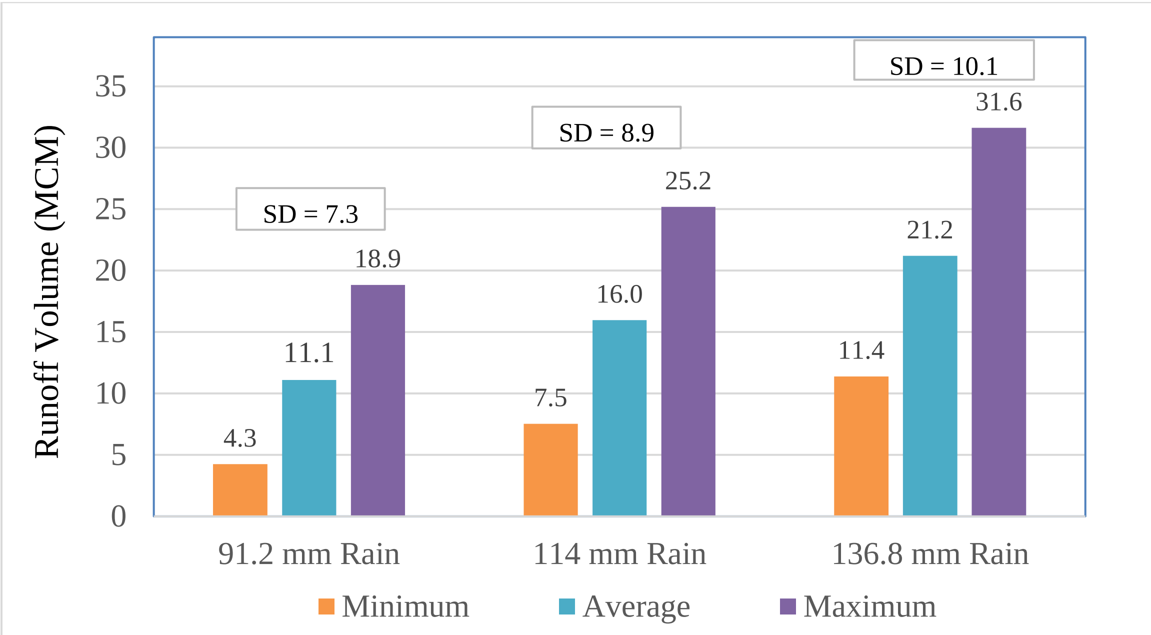


Figure 5.5: Variation of runoff volume with standard deviation (SD) for different rainfall depths in Abha basin (Runoff are estimated for a single event of rainfall, for 100-year return period)

For the CN values of 60, 75 and 90, average runoff volumes per event were 7.7, 15.3 and 25.2 MCM and their corresponding ranges were 4.3 – 11.4, 10.2 – 20.6 and 18.9 – 31.6 MCM respectively for (Figure 5.6).

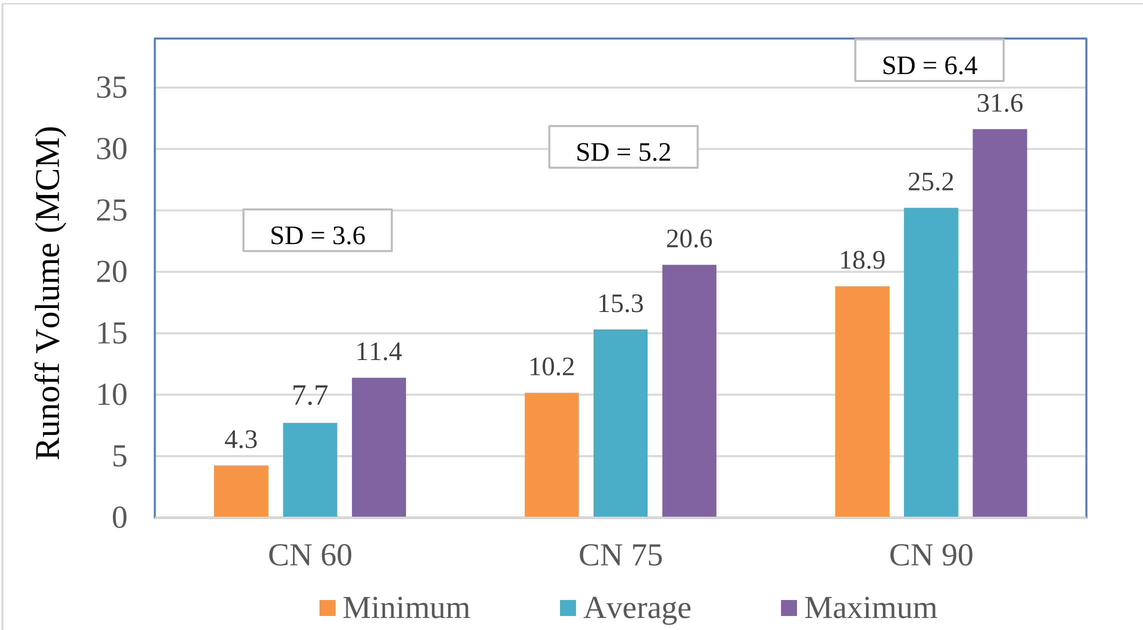


Figure 5.6: Variation of runoff volume with standard deviation (SD) for different curve numbers in Abha basin (Runoff are estimated for a single event of rainfall, for 100-year return period)

Variation of runoff per event for different return periods is presented in Figure 5.7. The averages of runoff in 9 scenarios for 25, 50 and 100-year rainfall events were 10.2, 13.1 and 16.1 MCM respectively while the corresponding ranges were 1.8 – 22.2, 2.9 – 26.9 and 4.3 – 31.6 MCM respectively.

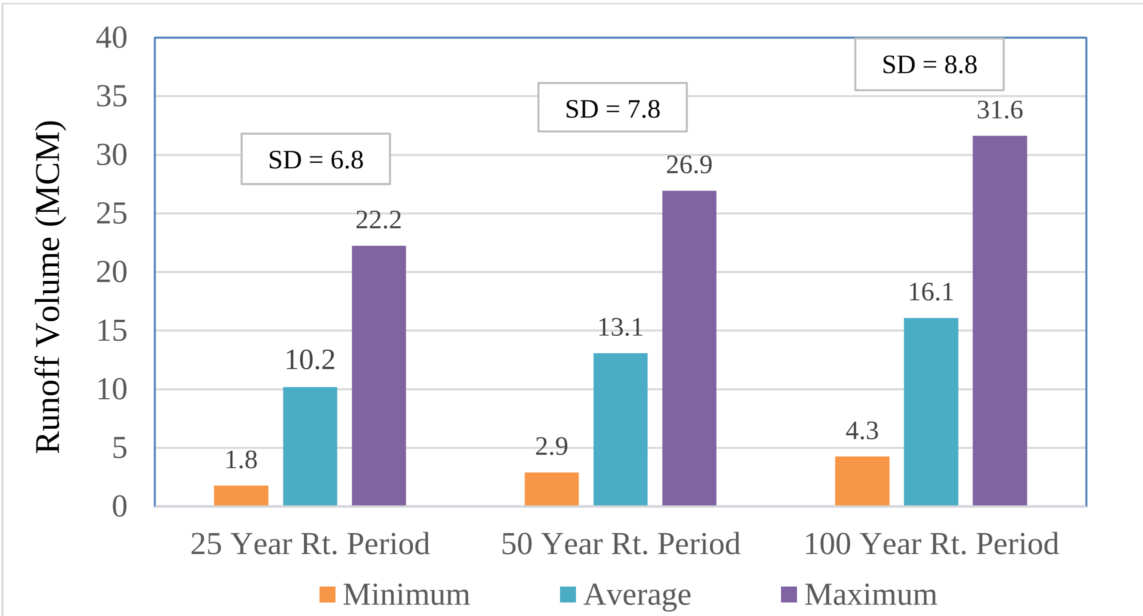


Figure 5.7: Variation of runoff volume with standard deviation (SD) for different return periods in Abha basin (Runoff are estimated for a single event of rainfall)

5.1.1.1Cost Saving

Replacement of equivalent amount of desalinated water by the surface runoff can save significant amounts of cost. The details are shown in Table B.**1** (Appendix B). For 25, 50 and 100 years' return periods, the average cost savings per event are US$ 12.1, 15.2 and 18.4 million with the ranges of US$ 0.9 – 35.4, 1.5 – 42.8 and 2.3 – 50.3 million respectively (Figure **5.8**).

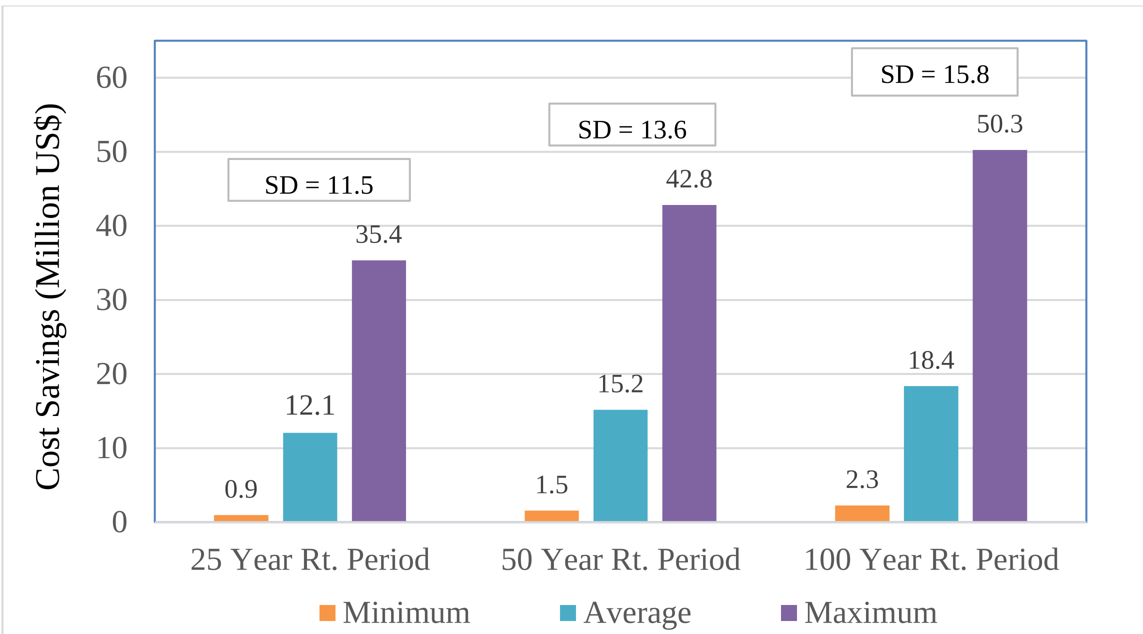


Figure 5.8: Cost savings with standard deviation (SD) by replacing desalinated water using runoff from Abha (Cost savings are estimated for a single event of rainfall)

5.1.1.2. Carbon Emission Reduction

Water supply in Abha is supplemented by the desalinated water from Al-Shuqaiq desalination plant in the coast of the Red Sea [88]. Approximately, 18.3 MCM of desalinated water is supplied to Abha in a year [28]. The Al-Shuqaiq plant is operated by MSF distillation process that cogenerates electricity [77]. On average, emission of CO_2 from desalinated water can be approximated to be 269.9 (= 18.3 million $m^3 \times$ 14.8 kg/m^3) million kg per year. The supply of desalinated water is likely to increase in near future [2], which may increase the amount of CO_2 emissions.

The average runoff per event from 25, 50 and 100 years' rainfall events were estimated to be 10.2, 13.1 and 16.1 MCM respectively and the corresponding ranges were 1.8 – 22.2, 2.9 – 26.9 and 4.3 – 31.6 MCM respectively (Figure **5.7**). The averages of runoff generations in all scenarios are much lower than the current supply of desalinated water, indicating that the runoff may be fully utilized. Replacement of equivalent amount of desalinated water by the surface runoff can reduce CO_2 emissions significantly (Appendix: Table B.**2**). For the return periods of 25, 50 and 100 years, the average CO_2 reductions per event are 168.1, 211.1 and 255.5 million kg respectively with the ranges of 24.6 – 346.9, 40.5 – 420.3 and 59.1 – 493.3 million kg respectively (Figure **5.9**).

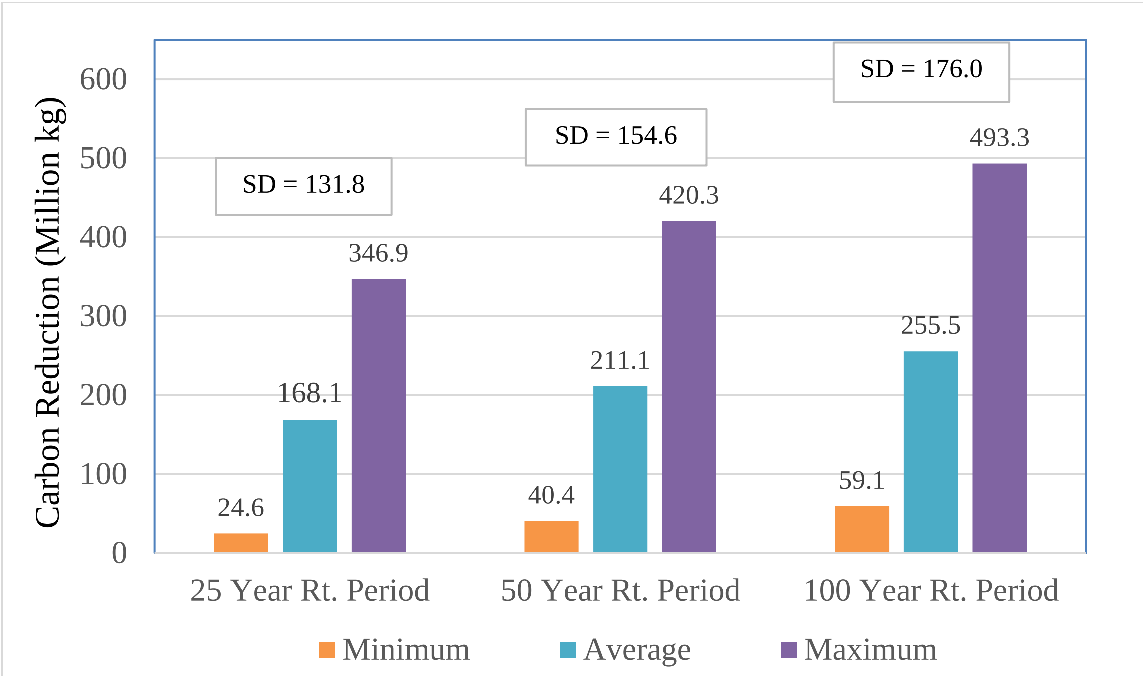


Figure 5.9: CO_2 reductions with standard deviation (SD) by replacing desalinated water using runoff from Abha (CO_2 reductions are estimated for a single event of rainfall)

5.1.2 Al-Baha

For 25-year return period and the low rainfall event (60.3 mm), the runoff per event was estimated in the range of 2.9 – 25.1 MCM, with an average of 12.9 MCM. For the most likely rainfall event (75.4 mm), this range was 6.1 – 33.9 MCM with an average of 18.9 MCM. For the high rainfall (90.5 mm), the runoff was estimated in the range of 10.3 – 42.9 MCM with an average of 25.6 MCM (Figure **5.10**).

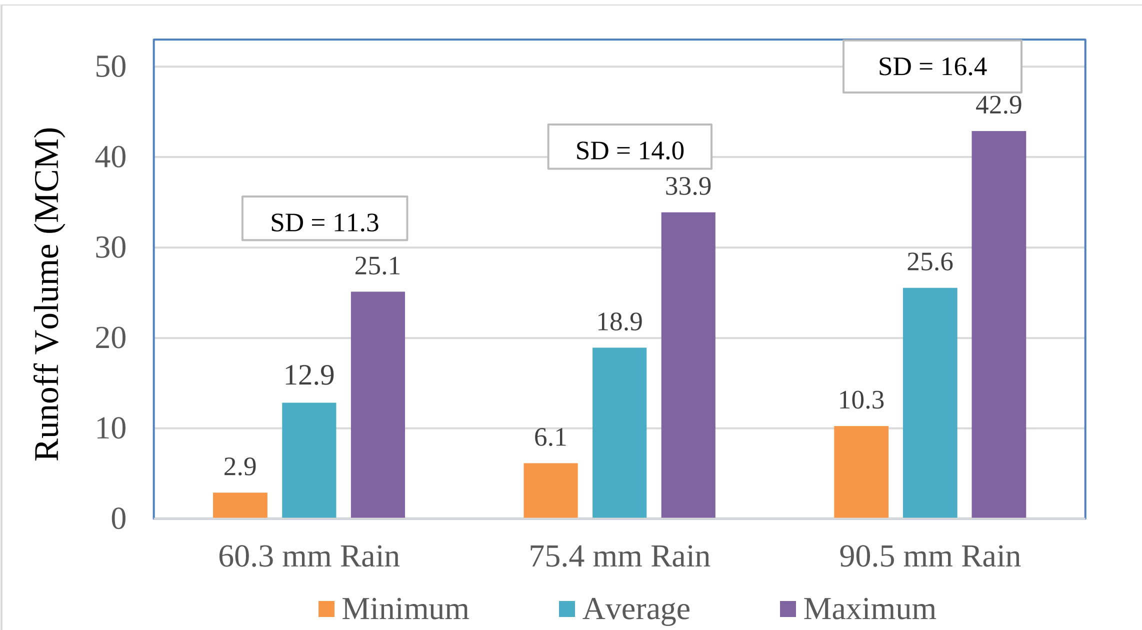


Figure 5.10: Variation of runoff volume with standard deviation (SD) for different rainfall depths in Al-Baha basin (Runoff are estimated for a single event of rainfall, for 25-year return period)

For the CN values of 62, 77 and 92, average runoff volumes per event were 6.4, 16.9 and 34.0 MCM and their corresponding ranges were 2.9 – 10.3, 10.6 – 23.5 and 25.1 – 42.9 MCM respectively (Figure **5.11**).

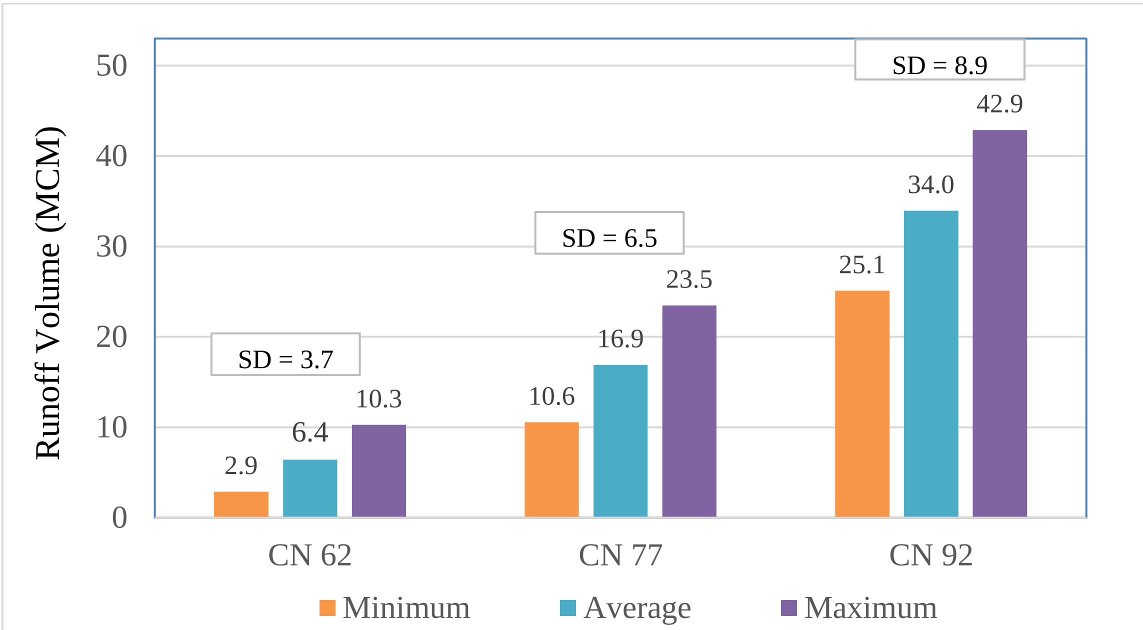


Figure 5.11: Variation of runoff volume with standard deviation (SD) for different curve numbers in Al-Baha basin (Runoff are estimated for a single event of rainfall, for 25-year return period)

For 50-year return period and the low rainfall event (70.56 mm), the runoff per event was estimated in the range of 5.0 – 31.1 MCM, with an average of 16.9 MCM. For the most likely rainfall event (88.2 mm), this range was 9.6 – 41.5 MCM, with an average of 24.5 MCM. For the high rainfall (105.8 mm), the runoff was estimated in the range of 15.2 – 52.2 MCM, with an average of 32.8 MCM (Figure **5.12**).

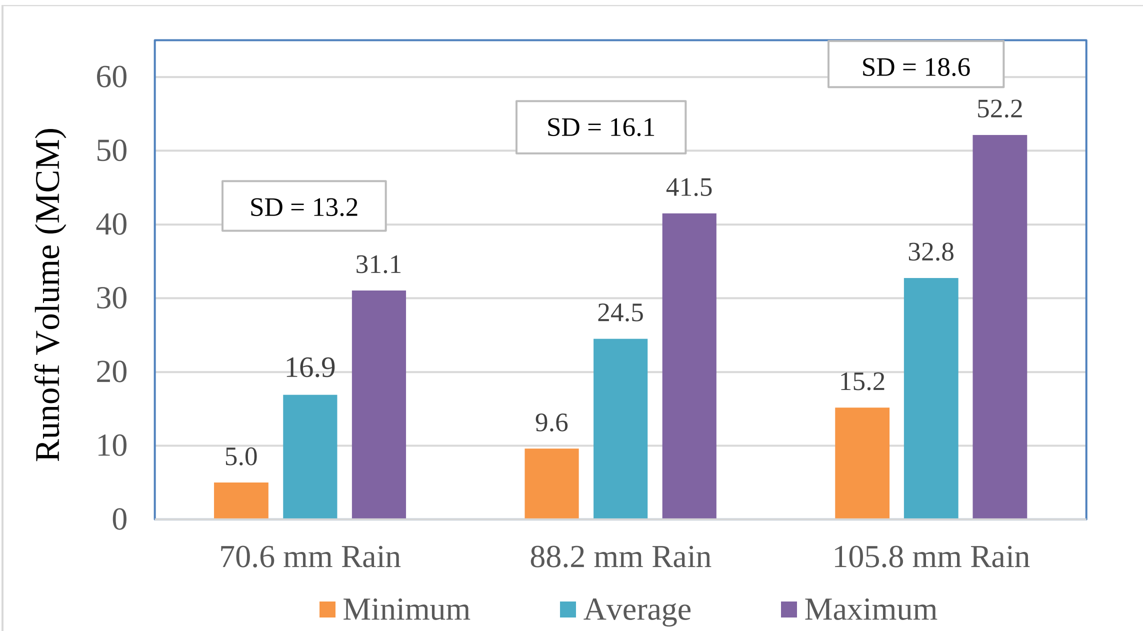


Figure 5.12: Variation of runoff volume with standard deviation (SD) for different rainfall depths in Al-Baha basin (Runoff are estimated for a single event of rainfall, for 50-year return period)

For the CN values of 62, 77 and 92, average runoff volumes per event were 9.9, 22.7 and 41.6 MCM and their corresponding ranges were 5.0 – 15.2, 14.6 – 30.9 and 31.1 – 52.2 MCM respectively (Figure **5.13**).

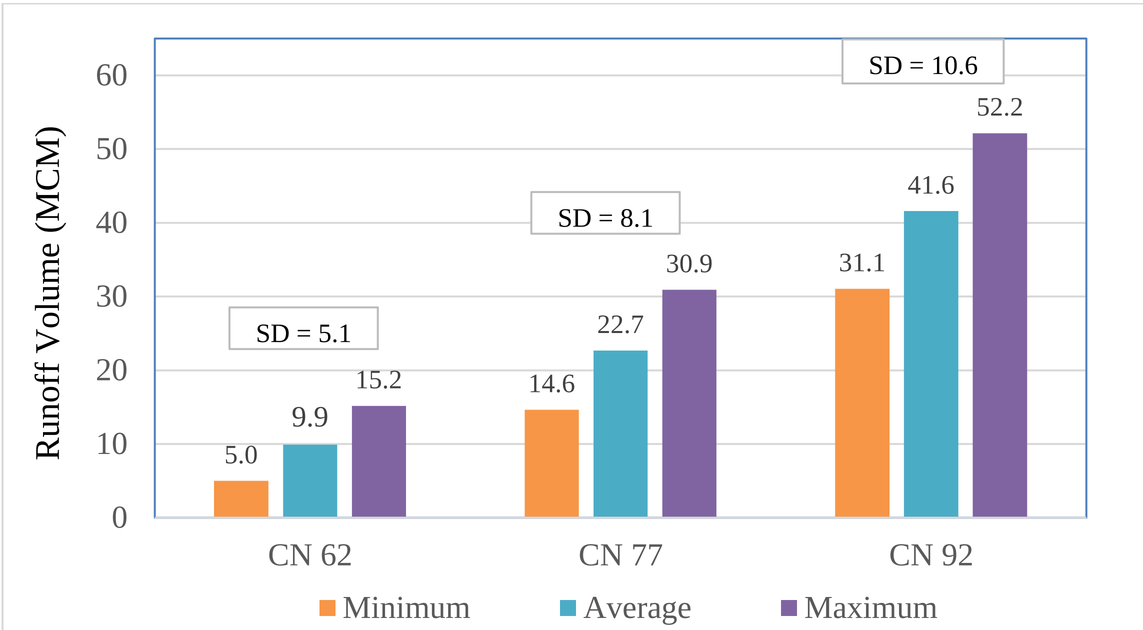


Figure 5.13: Variation of runoff volume with standard deviation (SD) for different curve numbers in Al-Baha basin (Runoff are estimated for a single event of rainfall, for 50-year return period)

For 100-year return period and the low rainfall event (80.8 mm), the runoff per event was estimated in the range of 7.5 – 37.1 MCM, with an average of 21.2 MCM. For the most likely rainfall event (101 mm), this range was 13.6 – 49.2 MCM, with an average of 30.4 MCM. For the high rainfall (121.2 mm), the runoff was estimated in the range of 20.7 – 61.5 MCM, with an average of 40.3 MCM (Figure **5.14**).

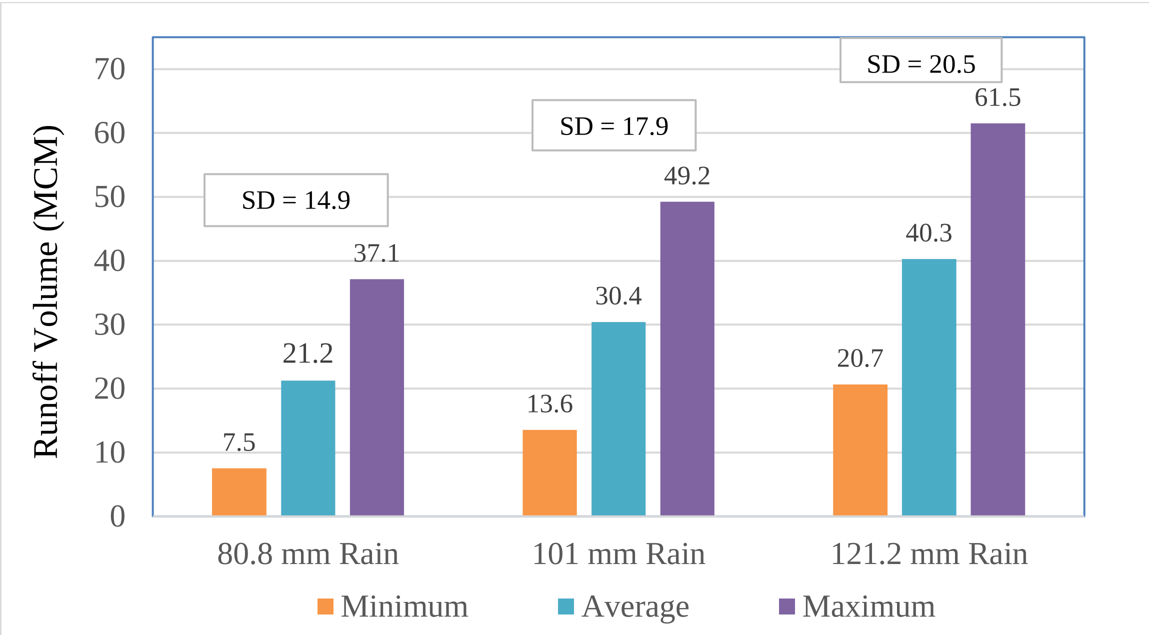


Figure 5.14: Variation of runoff volume with standard deviation (SD) for different rainfall depths in Al-Baha basin (Runoff are estimated for a single event of rainfall, for 100-year return period)

For the CN values of 62, 77 and 92, average runoff volumes per event were 13.9, 28.8 and 49.3 MCM and their corresponding ranges were 7.5 – 20.7, 19.1 – 38.7 and 37.1 – 61.5 MCM respectively (Figure **5.15**).

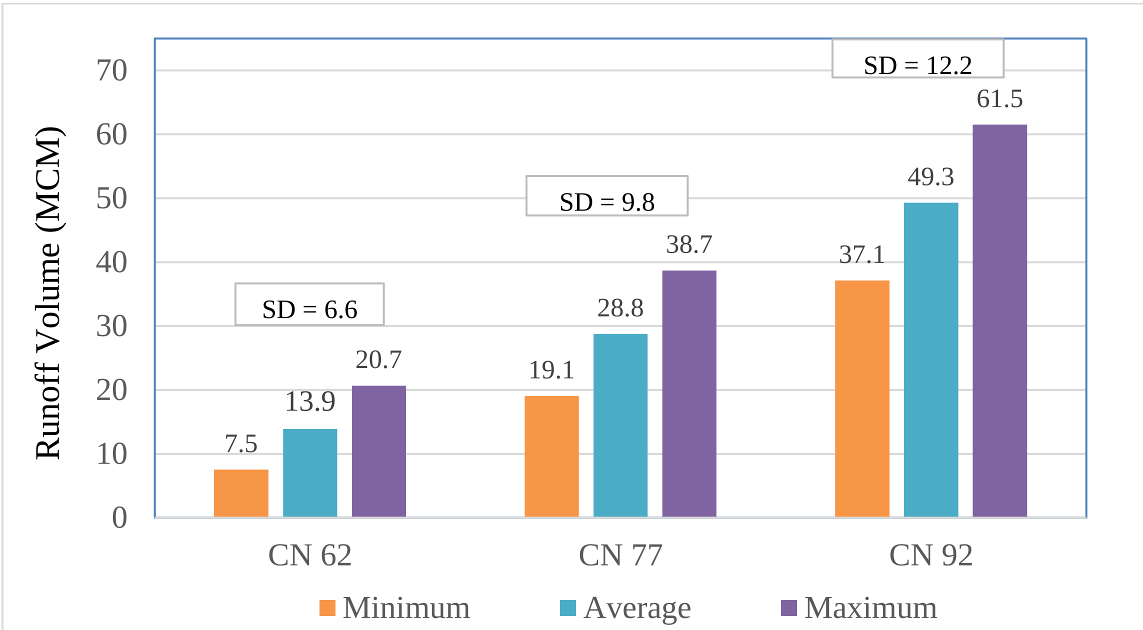


Figure 5.15: Variation of runoff volume with standard deviation (SD) for different curve numbers in Al-Baha basin (Runoff are estimated for a single event of rainfall, for 100-year return period)

Variation of runoff per event for different return periods is presented in Figure **5.16**. The averages of runoff in 9 scenarios for 25, 50 and 100-year rainfall events were 19.1, 24.7 and 30.7 MCM respectively while the corresponding ranges were 2.9 – 42.9, 5.0 – 52.2 and 7.5 – 61.5 MCM respectively.

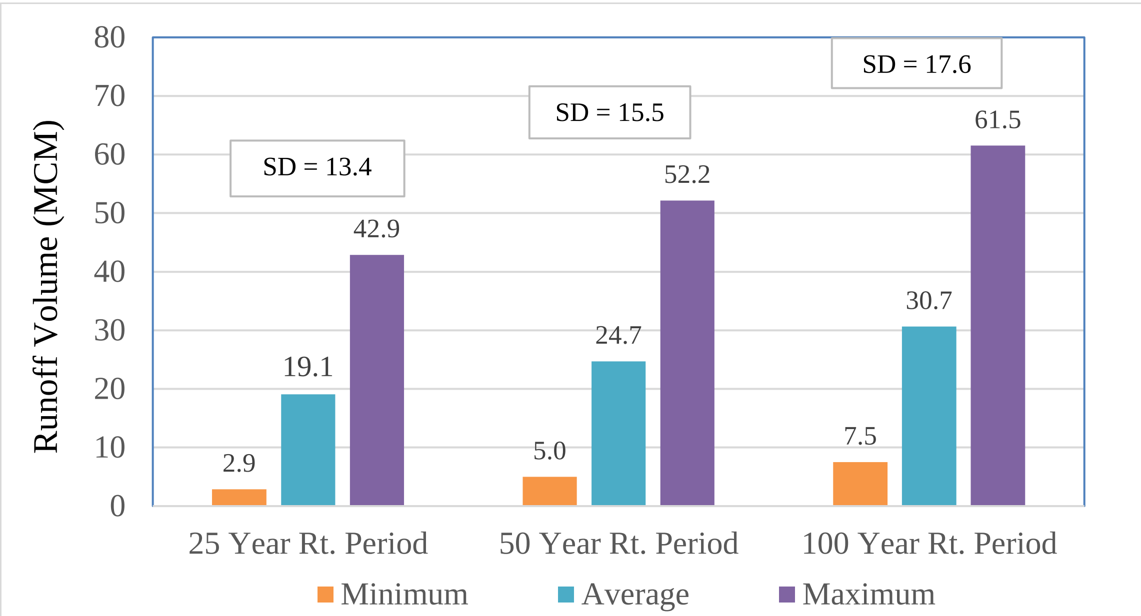


Figure 5.16: Variation of runoff volume with standard deviation (SD) for different return periods in Al-Baha basin (Runoff are estimated for a single event of rainfall)

5.1.2.1 Cost Saving

Replacement of equivalent amount of desalinated water by the surface runoff can save significant amounts of cost. The details are shown in Table B.**3** (Appendix B). For 25, 50 and 100 years' return periods, the average cost savings per event are US$ 21.4, 26.9 and 32.8 million with the ranges of US$ 1.3 – 65.1, 2.3 – 79.1 and 3.4 – 93.3 million respectively (Figure **5.17**).

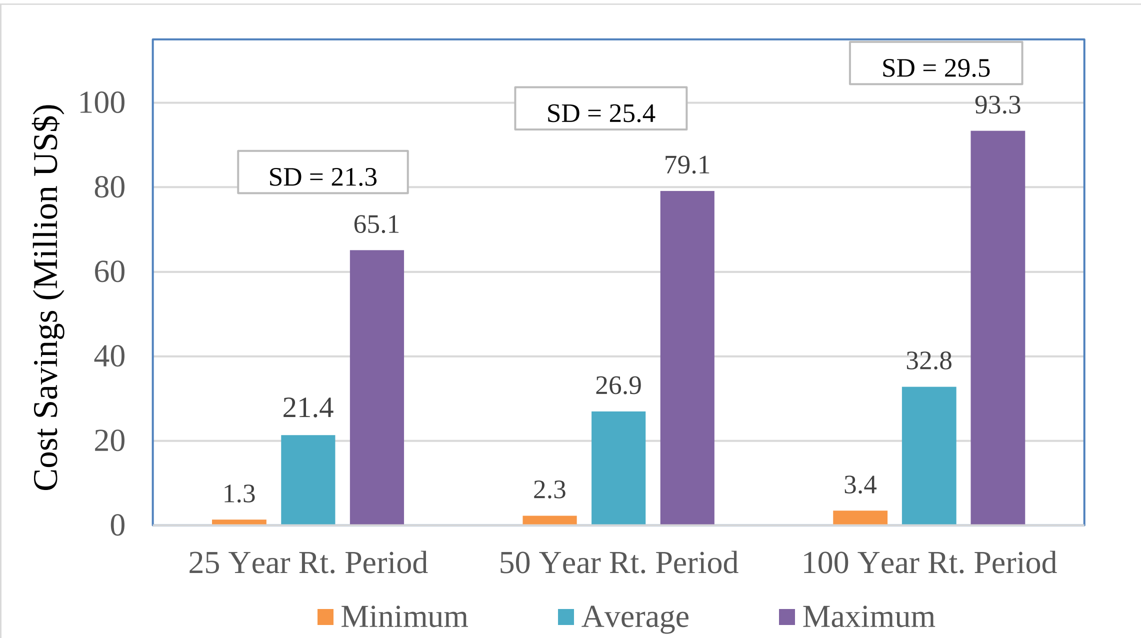


Figure 5.17: Cost savings with standard deviation (SD) by replacing desalinated water using runoff from Al-Baha (Cost savings are estimated for a single event of rainfall)

5.1.2.2 Carbon Emission Reduction

Water supply in Al-Baha is supplemented by the desalinated water from Al-Shuaiba desalination plant (3rd phase) in the coast of the Red Sea [28]. Approximately, 12.3 MCM of desalinated water is supplied to Al-Baha in a year [28]. The Al-Shuaiba plant (3rd phase) is operated by MSF distillation process that cogenerates electricity [77]. On average, emission of CO_2 from desalinated water can be reduced by 181.4 (= 12.3 million $m^3 \times$ 14.8 kg/m^3) million kg per year.

The average runoff per event from 25, 50 and 100 years' rainfall events were estimated to be 19.1, 24.7 and 30.7 MCM respectively and the corresponding ranges were 2.9 – 42.9, 5.0 – 52.2 and 7.5 – 60.5 MCM respectively (Figure **5.16**). Replacement of equivalent amount of desalinated water by the surface runoff can reduce CO_2 emissions significantly (Appendix: Table B.**4**). For the return periods of 25, 50 and 100 years, the average CO_2 reductions per event are 319.0, 402.6 and 490.1 million kg respectively with the ranges of 40.2 – 669.1, 69.5 – 813.7 and 104.5 – 959.6 million kg respectively (Figure **5.18**).

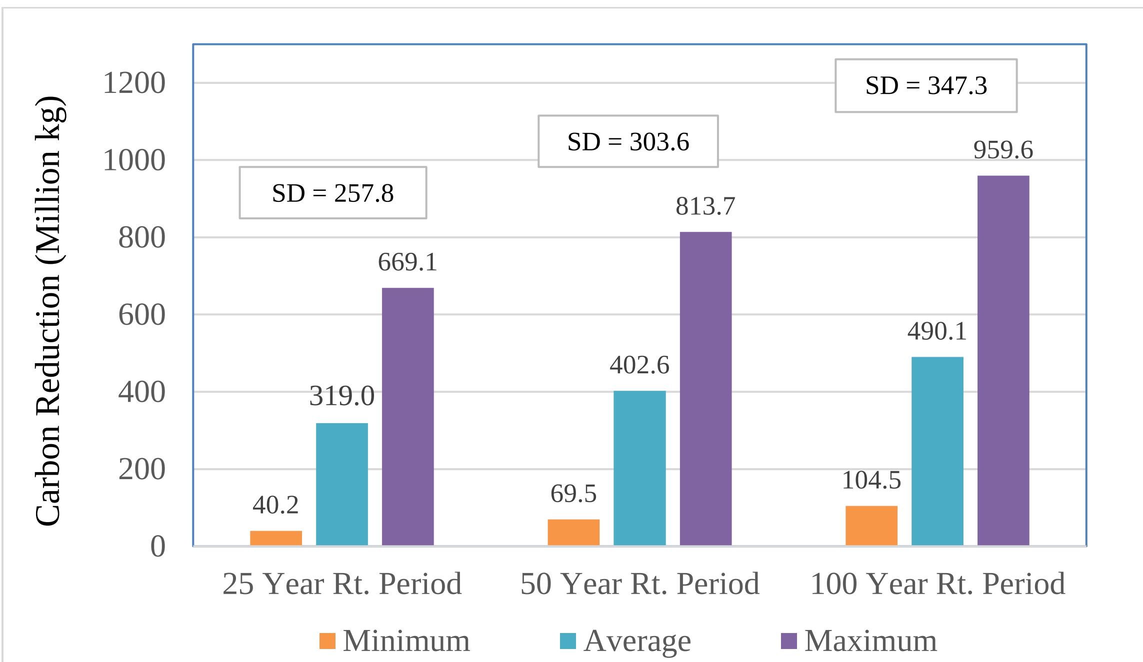


Figure 5.18: CO_2 reductions with standard deviation (SD) by replacing desalinated water using runoff from Al-Baha (CO_2 reductions are estimated for a single event of rainfall)

5.1.3 Bisha

For 25-year return period and the low rainfall event (29.1 mm), the runoff per event was estimated in the range of 0.3 – 2.4 MCM, with an average of 0.9 MCM. For the most likely rainfall event (36.4 mm), this range was 0.8 – 3.7 MCM, with an average of 1.5 MCM. For the high rainfall (43.7 mm), the runoff was estimated in the range of 1.4 – 5.1 MCM, with an average of 2.2 MCM (Figure **5.19**).

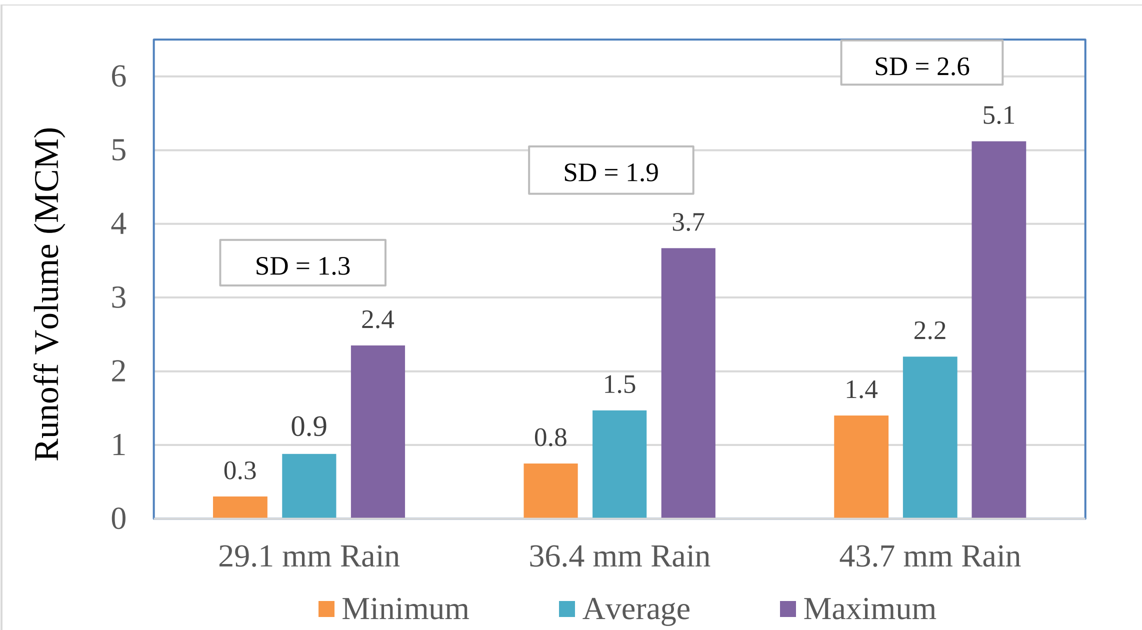


Figure 5.19: Variation of runoff volume with standard deviation (SD) for different rainfall depths in Bisha basin (Runoff are estimated for a single event of rainfall, for 25-year return period)

For the CN values of 58, 73 and 88, average runoff volumes per event were 0.1, 0.8 and 3.7 MCM and their corresponding ranges were 0.1 – 0.1, 0.3 – 1.4 and 2.4 – 5.1 MCM respectively (Figure **5.20**).

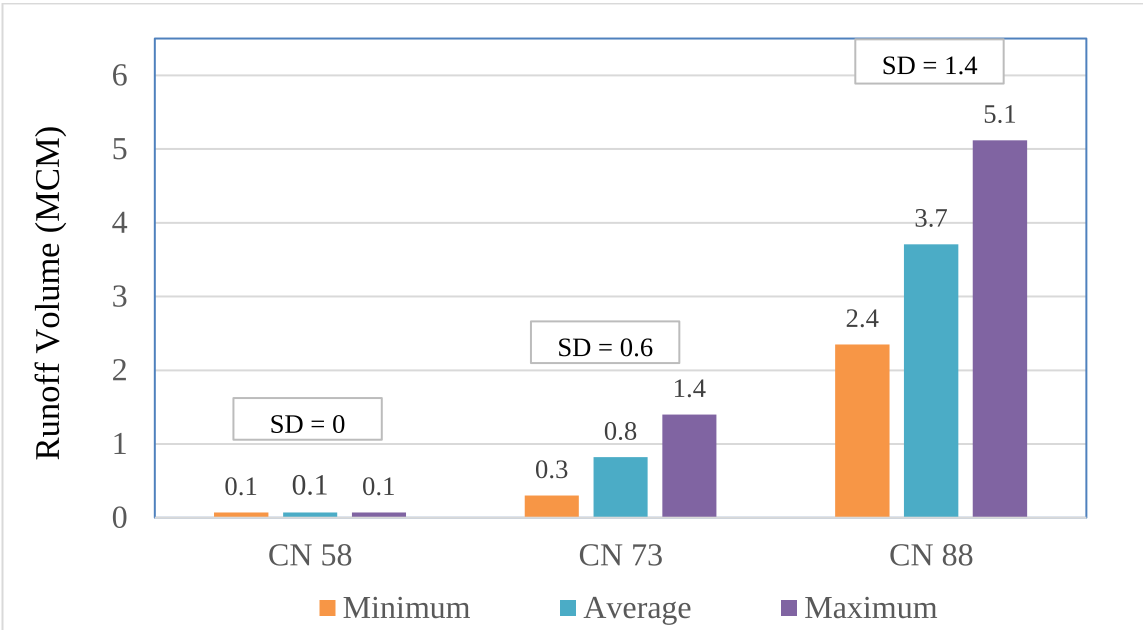


Figure 5.20: Variation of runoff volume with standard deviation (SD) for different curve numbers in Bisha basin (Runoff are estimated for a single event of rainfall, for 25-year return period)

For 50-year return period and the low rainfall event (33.1 mm), the runoff per event was estimated in the range of 0.5 – 3.1 MCM, with an average of 1.2 MCM. For the most likely rainfall event (41.4 mm), this range was 1.2 – 4.7 MCM, with an average of 2.0 MCM. For the high rainfall (49.7 mm), the runoff was estimated in the range of 2.1 – 6.4 MCM, with an average of 2.9 MCM (Figure **5.21**).

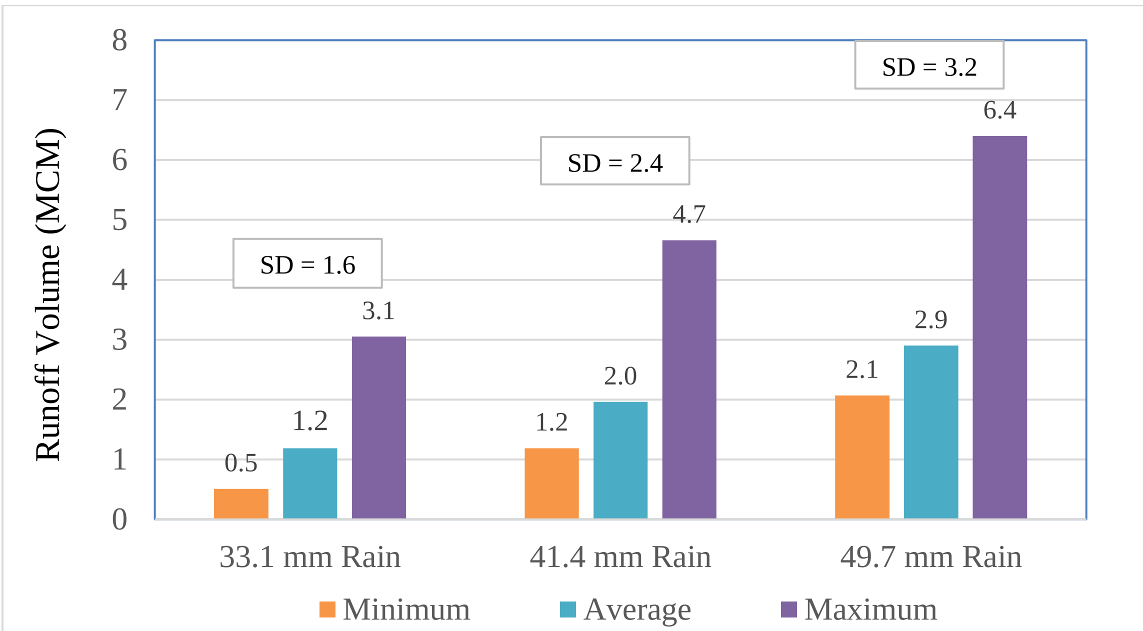


Figure 5.21: Variation of runoff volume with standard deviation (SD) for different rainfall depths in Bisha basin (Runoff are estimated for a single event of rainfall, for 50-year return period)

For the CN values of 58, 73 and 88, average runoff volumes per event were 0.2, 1.3 and 4.7 MCM and their corresponding ranges were 0.2 – 0.2, 0.5 – 2.1 and 3.1 – 6.4 MCM respectively (Figure **5.22**).

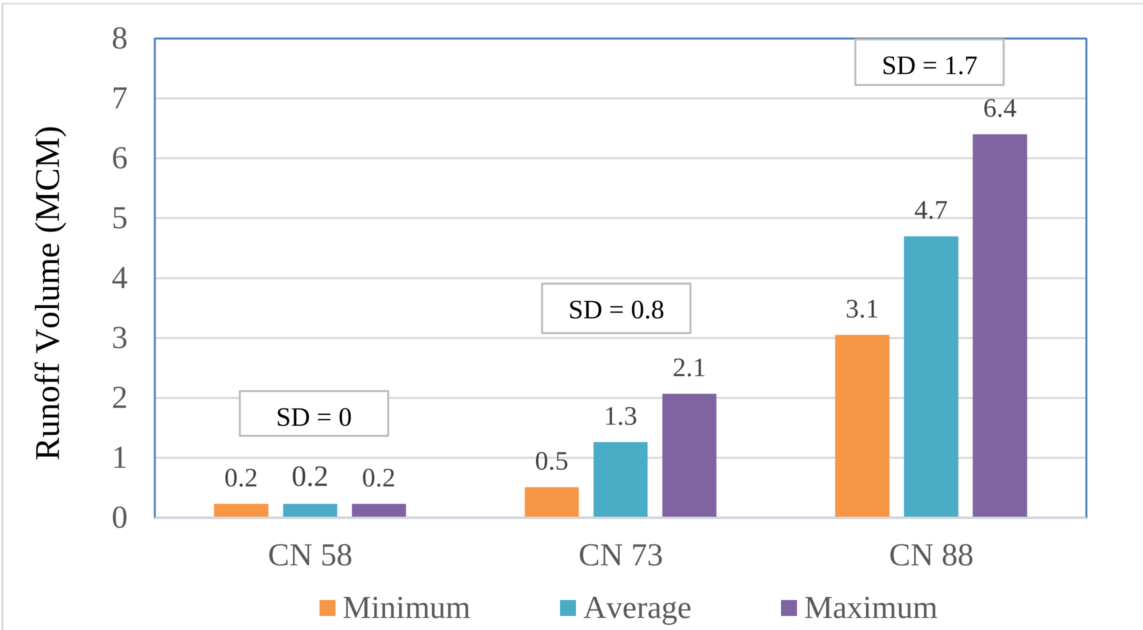


Figure 5.22: Variation of runoff volume with standard deviation (SD) for different curve numbers in Bisha basin (Runoff are estimated for a single event of rainfall, for 50-year return period)

For 100-year return period and the low rainfall event (37.1 mm), the runoff per event was estimated in the range of 0.8 – 3.8 MCM, with an average of 1.5 MCM. For the most likely rainfall event (46.4 mm), this range was 1.7 – 5.7 MCM, with an average of 2.5 MCM. For the high rainfall (55.7 mm), the runoff was estimated in the range of 2.8 – 7.7 MCM, with an average of 3.7 MCM (Figure **5.23**).

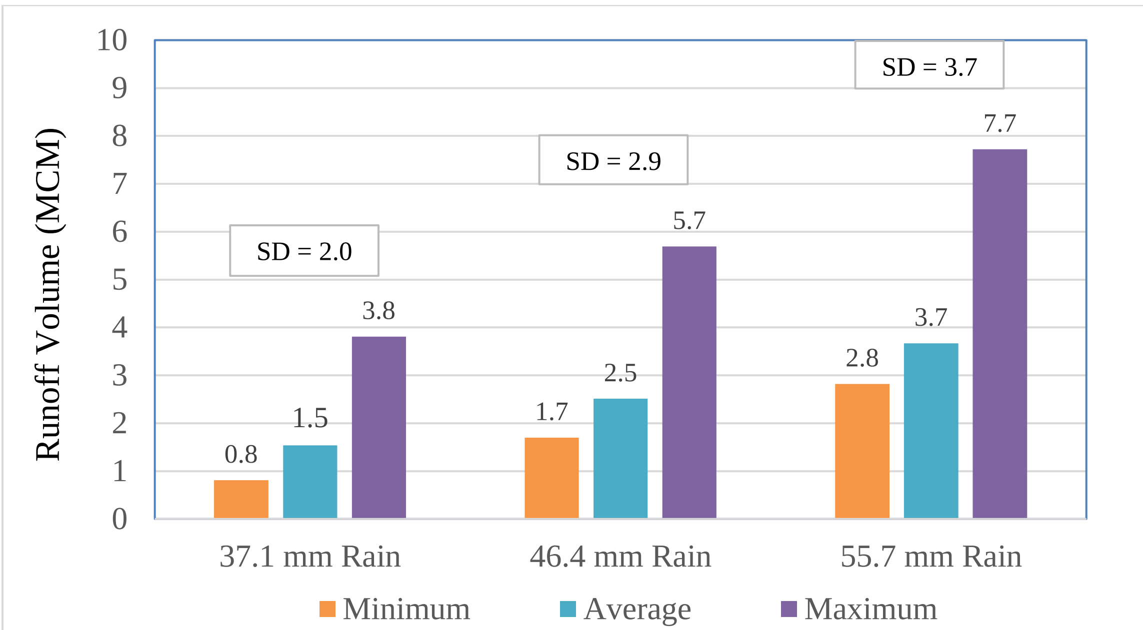


Figure 5.23: Variation of runoff volume with standard deviation (SD) for different rainfall depths in Bisha basin (Runoff are estimated for a single event of rainfall, for 100-year return period)

For the CN values of 58, 73 and 88, average runoff volumes per event were 0.5, 1.8 and 5.7 MCM and their corresponding ranges were 0.5 – 0.5, 0.8 – 2.8 and 3.8 – 7.7 MCM respectively (Figure **5.24**).

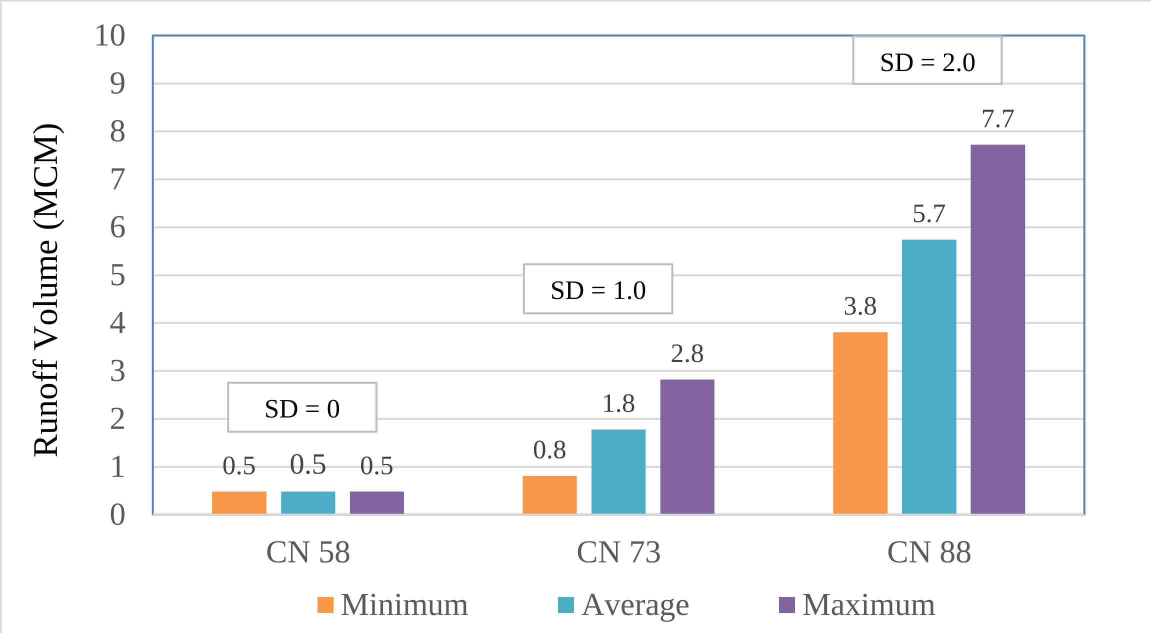


Figure 5.24: Variation of runoff volume with standard deviation (SD) for different curve numbers in Bisha basin (Runoff are estimated for a single event of rainfall, for 100-year return period)

Variation of runoff per event for different return periods is presented in Figure **5.25**. The averages of runoff in 9 scenarios for 25, 50 and 100-year rainfall events were 1.5, 2.0 and 2.6 MCM respectively while the corresponding ranges were 0.1 – 5.1, 0.2 – 6.4 and 0.5 – 7.7 MCM respectively.

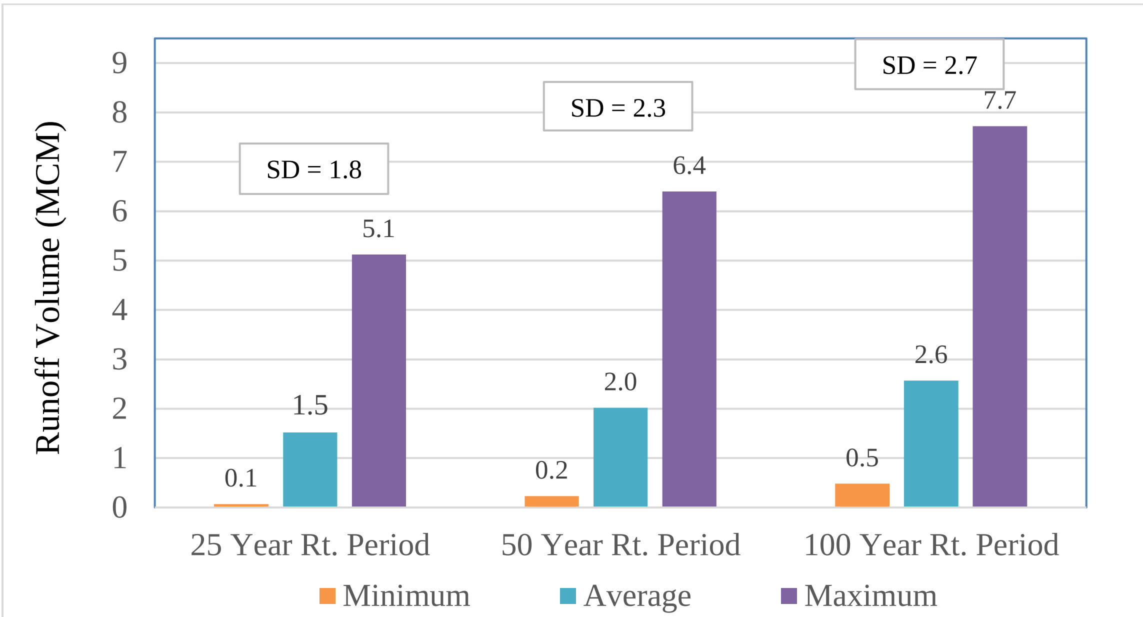


Figure 5.25: Variation of runoff volume with standard deviation (SD) for different return periods in Bisha basin (Runoff are estimated for a single event of rainfall)

5.1.3.1 Cost Saving

Replacement of equivalent amount of desalinated water by the surface runoff can save significant amounts of cost. The details are shown in Table B.**5** (Appendix B). For 25, 50 and 100 years' return periods, the average cost savings per event are US$ 2.7, 3.4 and 4.3 million with the ranges of US$ 0.1 – 8.8, 0.2 – 11.0 and 0.3 – 13.3 million respectively (Figure **5.26**).

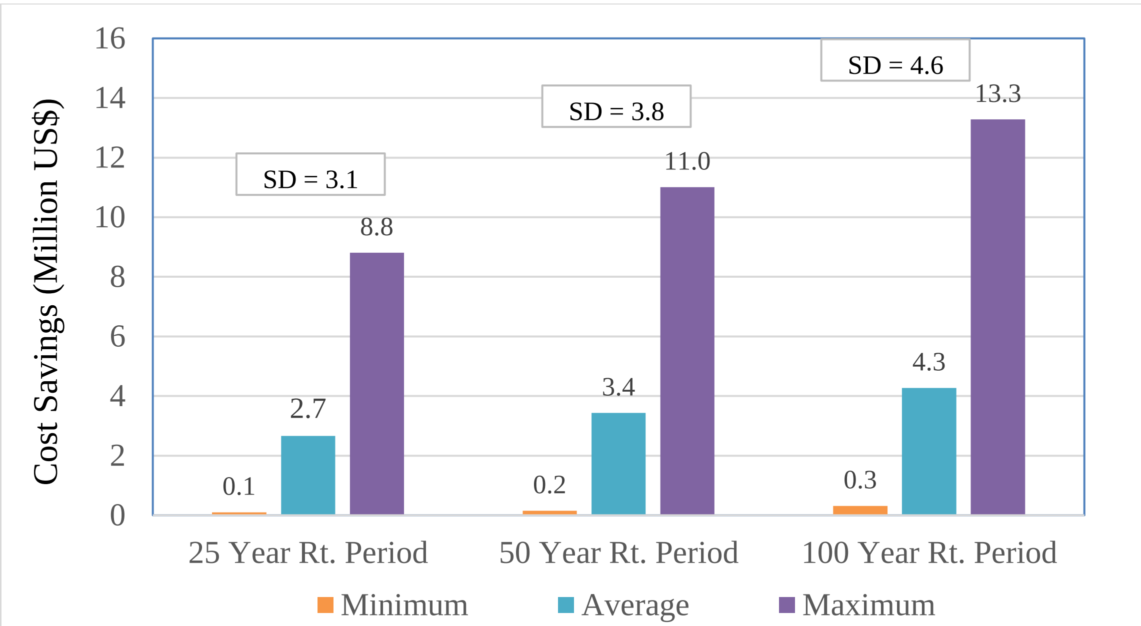


Figure 5.26: Cost savings with standard deviation (SD) by replacing desalinated water using runoff from Bisha (Cost savings are estimated here for a single event of rainfall)

5.1.3.2 Carbon Emission Reduction

Bisha is not dependent on desalinated water for drinking purpose but on runoff water, stored by King Fahd dam [89]. But, it can be predicted that in near future dependency on desalinated water may grow because of increasing consumers, which will let the process to emit in average 14.8 kg CO_2 (considering MSF cogeneration process) to the environment in producing 1 m^3 of water.

The average runoff per event from the 25, 50 and 100 years' rainfall events were estimated to be 1.5, 2.0 and 2.6 MCM respectively and the corresponding ranges were 0.1 – 5.1, 0.2 – 6.4 and 0.5 – 7.2 MCM respectively (Figure **5.25**). Replacement of equivalent amount of desalinated water by the surface runoff can reduce CO_2 emissions significantly (Appendix: Table B.**6**). For the return periods of 25, 50 and 100 years, the average CO_2 reductions per event are 33.0, 42.5 and 53.0 million kg respectively with the ranges of 1.0 – 79.9, 3.2 – 99.8 and 6.7 – 120.4 million kg respectively (Figure **5.27**).

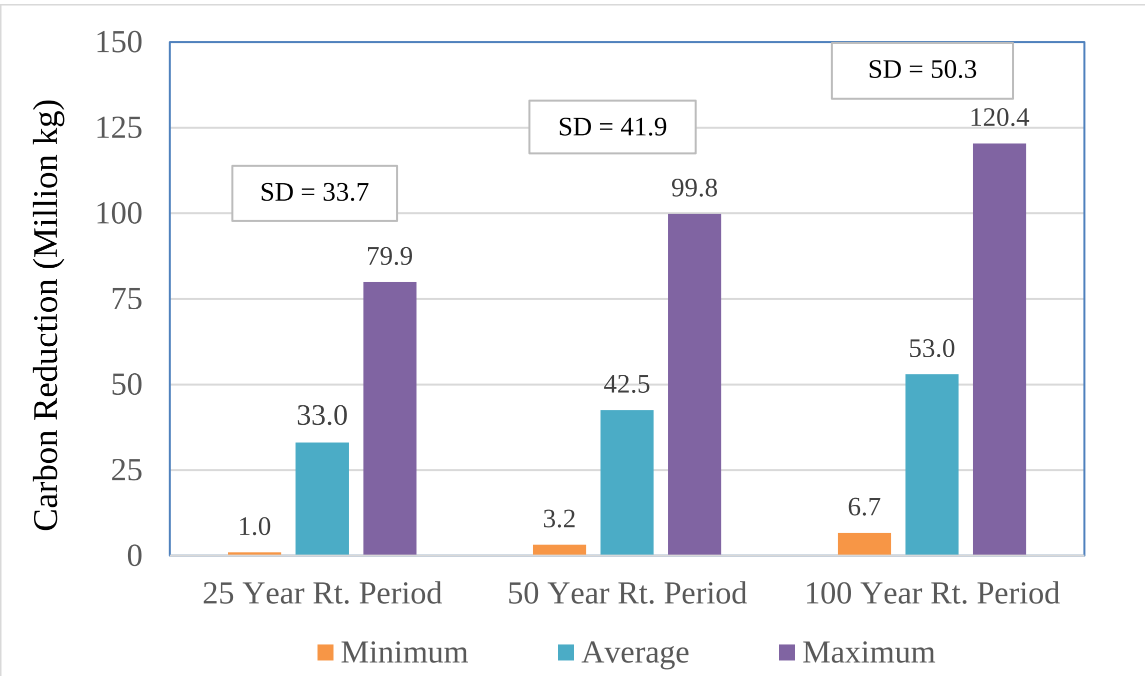


Figure 5.27: CO_2 reductions with standard deviation (SD) by replacing desalinated water using runoff from Bisha (CO_2 reductions are estimated for a single event of rainfall)

5.1.4 Jizan

For 25-year return period and the low rainfall event (55.8 mm), the runoff per event was estimated in the range of 0.5 – 8.8 MCM, with an average of 4.2 MCM. For the most likely rainfall event (69.8 mm), this range was 1.4 – 12.6 MCM, with an average of 6.5 MCM. For the high rainfall (83.8 mm), the runoff was estimated in the range of 2.8 – 16.6 MCM, with an average of 9.2 MCM (Figure **5.28**).

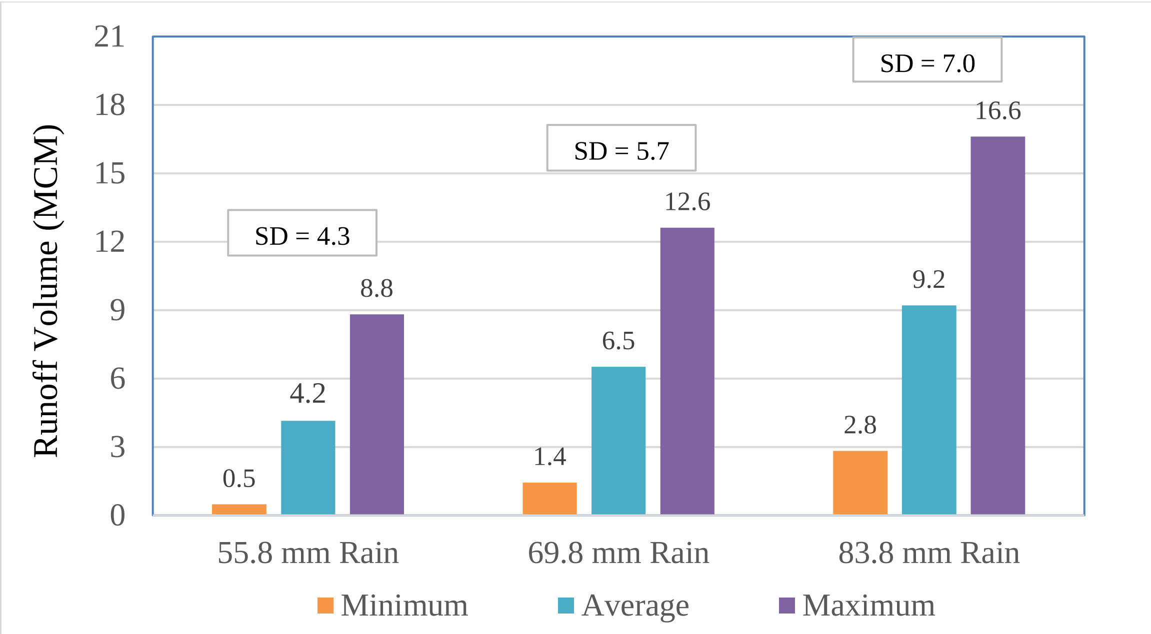


Figure 5.28: Variation of runoff volume with standard deviation (SD) for different rainfall depths in Jizan basin (Runoff are estimated for a single event of rainfall, for 25-year return period)

For the CN values of 57, 72 and 87, average runoff volumes per event were 1.6, 5.6 and 12.7 MCM and their corresponding ranges were 0.5 – 2.8, 3.2 – 8.2 and 8.8 – 16.6 MCM respectively (Figure **5.29**).

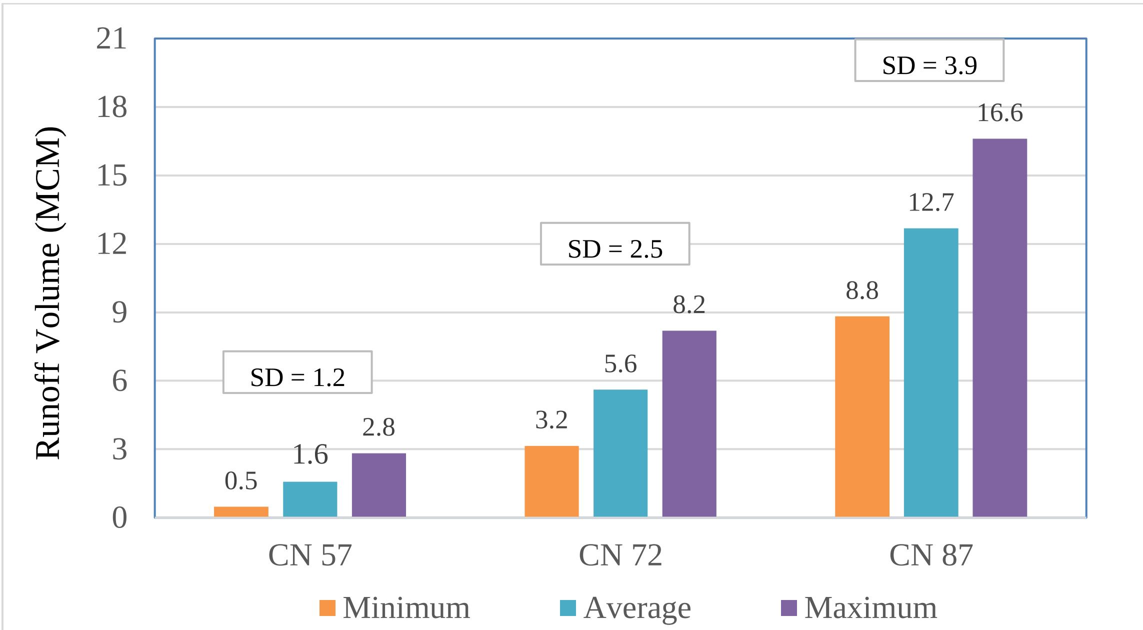


Figure 5.29: Variation of runoff volume with standard deviation (SD) for different curve numbers in jizan basin (Runoff are estimated for a single event of rainfall, for 25-year return period)

For 50-year return period and the low rainfall event (63.7 mm), the runoff per event was estimated in the range of 1.0 – 11.0 MCM, with an average of 5.5 MCM. For the most likely rainfall event (79.6 mm), this range was 2.4 – 15.5 MCM, with an average of 8.5 MCM. For the high rainfall (95.5 mm), the runoff was estimated in the range of 4.3 – 20.2 MCM, with an average of 11.8 MCM (Figure **5.30**).

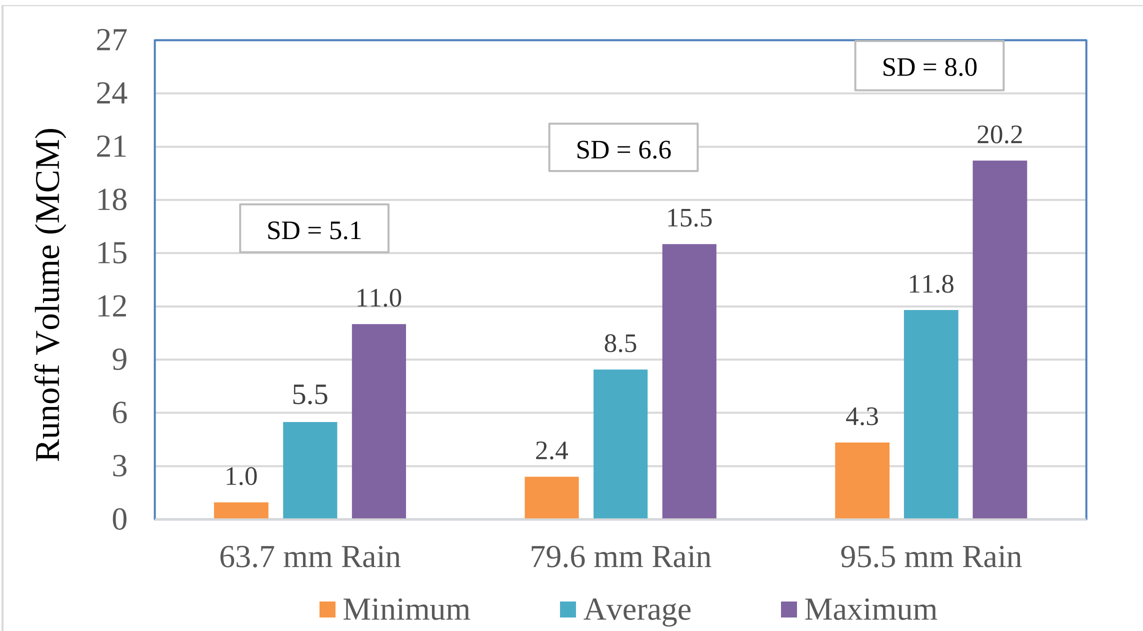


Figure 5.30: Variation of runoff volume with standard deviation (SD) for different rainfall depths in Jizan basin (Runoff are estimated for a single event of rainfall, for 50-year return period)

For the CN values of 57, 72 and 87, average runoff volumes per event were 2.6, 7.6 and 15.6 MCM and their corresponding ranges were 1.0 – 4.3, 4.5 – 10.8 and 11.0 – 20.2 MCM respectively (Figure **5.31**).

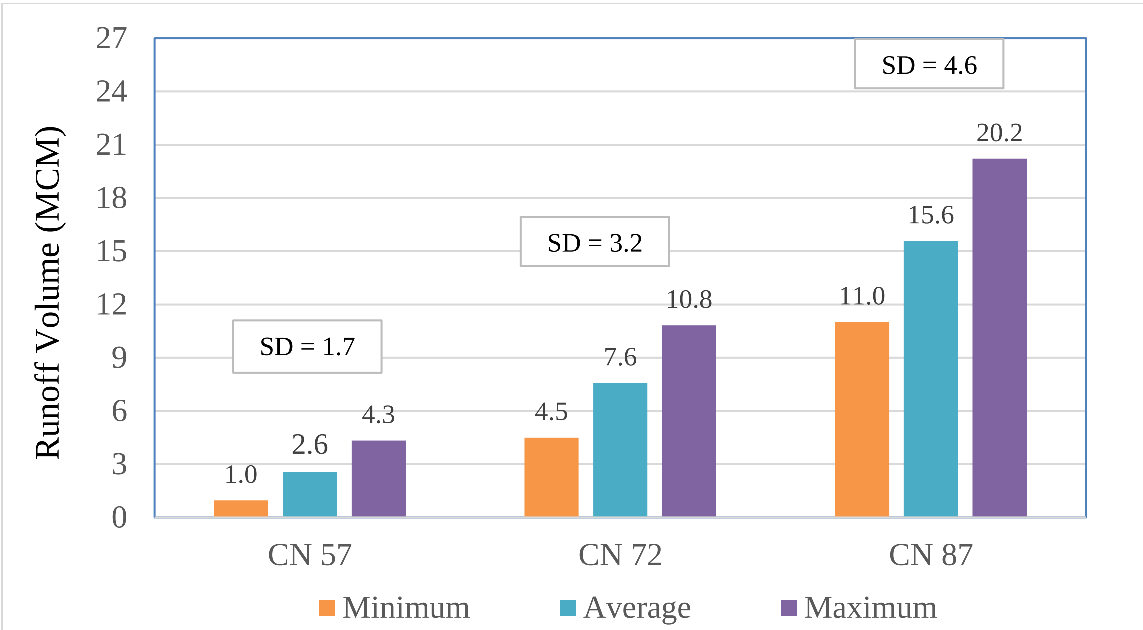


Figure 5.31: Variation of runoff volume with standard deviation (SD) for different curve numbers in Jizan basin (Runoff are estimated for a single event of rainfall, for 50-year return period)

For 100-year return period and the low rainfall event (71.7 mm), the runoff per event was estimated in the range of 1.6 – 13.3 MCM, with an average of 6.9 MCM. For the most likely rainfall event (89.6 mm), this range was 3.6 – 18.5 MCM, with an average of 10.5 MCM. For the high rainfall (107.5 mm), the runoff was estimated in the range of 6.0 – 23.8 MCM, with an average of 14.5 MCM (Figure **5.32**).

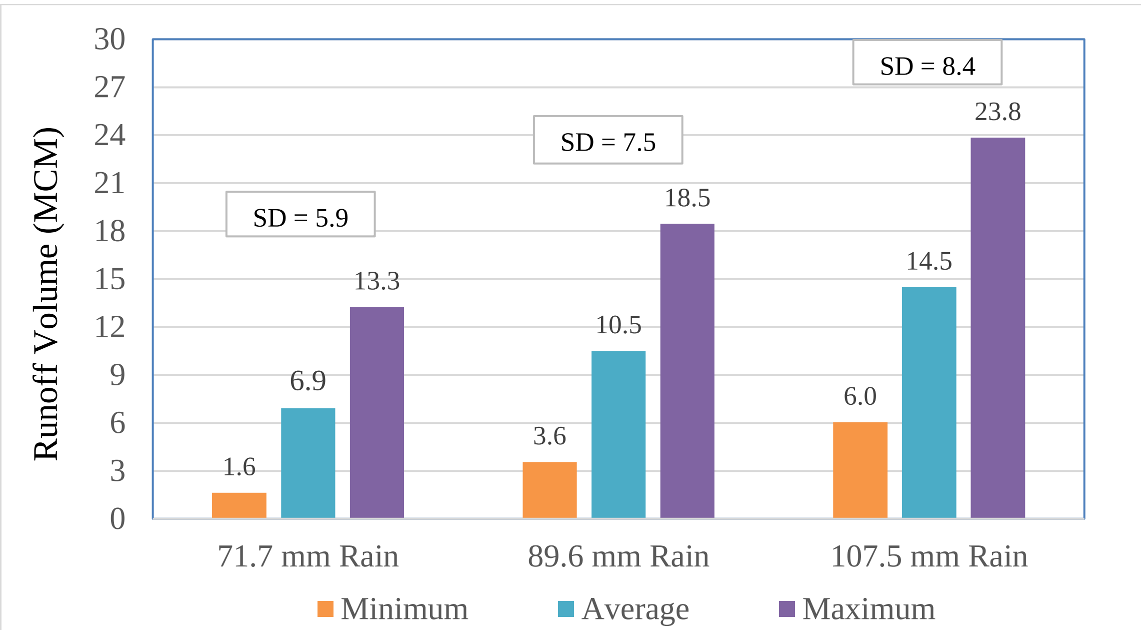


Figure 5.32: Variation of runoff volume with standard deviation (SD) for different rainfall depths in Jizan basin (Runoff are estimated for a single event of rainfall, for 100-year return period)

For the CN values of 57, 72 and 87, average runoff volumes per event were 3.7, 9.7 and 18.5 MCM and their corresponding ranges were 1.6 – 6.0, 5.9 – 13.6 and 13.3 – 23.8 MCM respectively (Figure **5.33**).

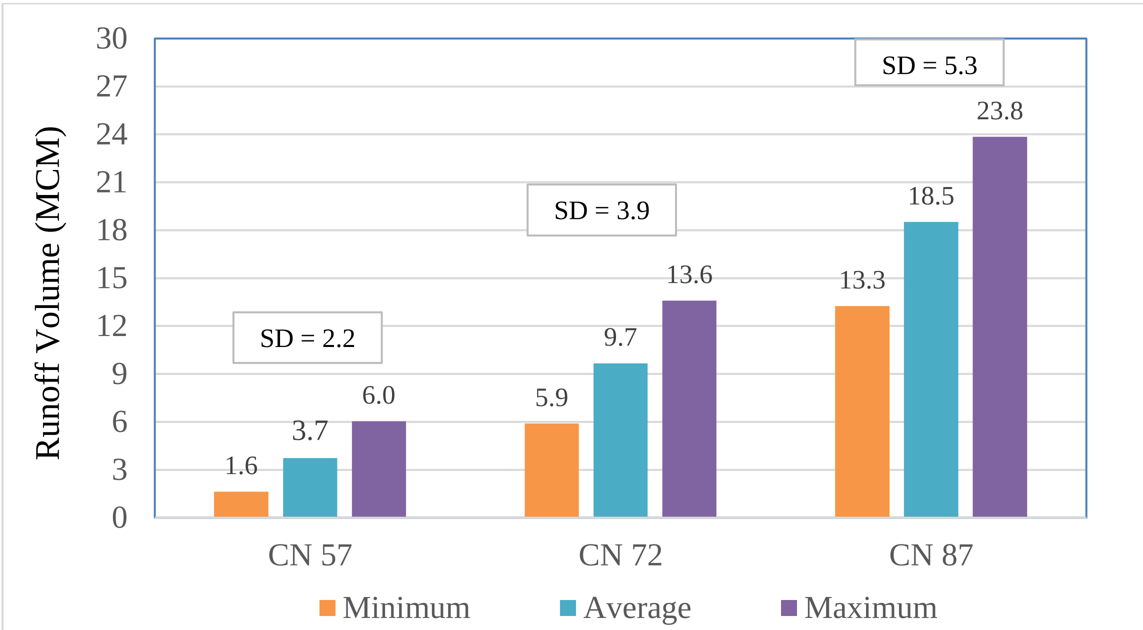


Figure 5.33: Variation of runoff volume with standard deviation (SD) for different curve numbers in Jizan basin (Runoff are estimated for a single event of rainfall, for 100-year return period)

Variation of runoff per event for different return periods is presented in Figure **5.34**. The averages of runoff in 9 scenarios for 25, 50 and 100-year rainfall events were 6.6, 8.6 and 10.6 MCM respectively while the corresponding ranges were 0.5 – 16.6, 1.0 – 20.2 and 1.6 – 23.8 MCM respectively.

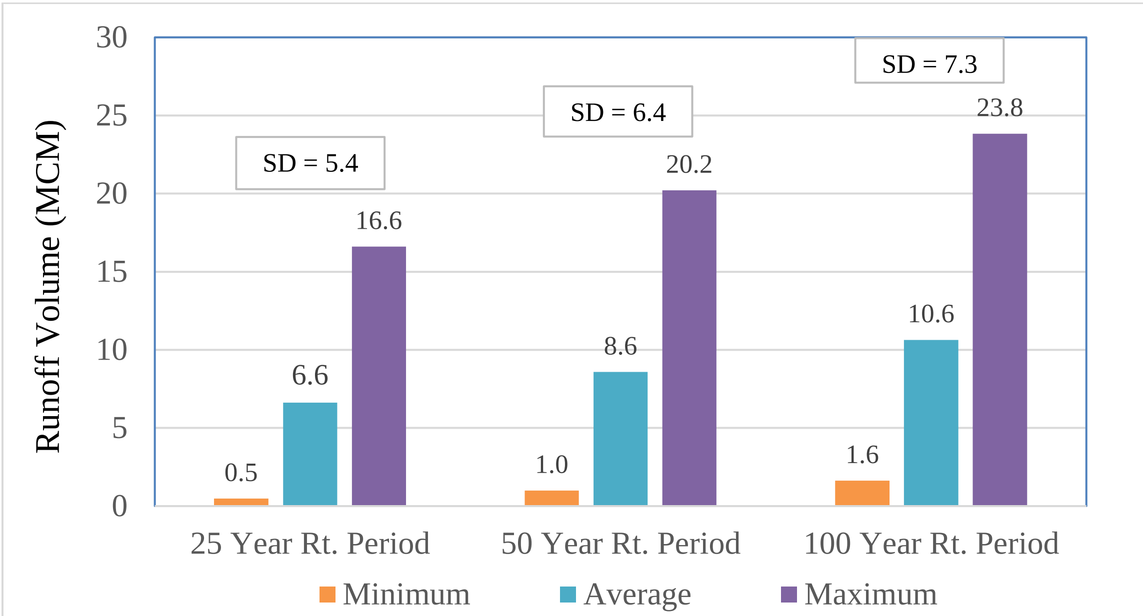


Figure 5.34: Variation of runoff volume with standard deviation (SD) for different return periods in Jizan basin (Runoff are estimated for a single event of rainfall)

5.1.4.1Cost Saving

Replacement of equivalent amount of desalinated water by the surface runoff can save significant amounts of cost. The details are shown in Table B.**7** (Appendix B). For 25, 50 and 100 years' return period, the average cost savings per event are US$ 9.5, 11.9 and 14.4 million with the ranges of US$ 0.3 – 28.7, 0.6 – 34.9 and 1.1 – 41.1 million respectively (Figure **5.35**).

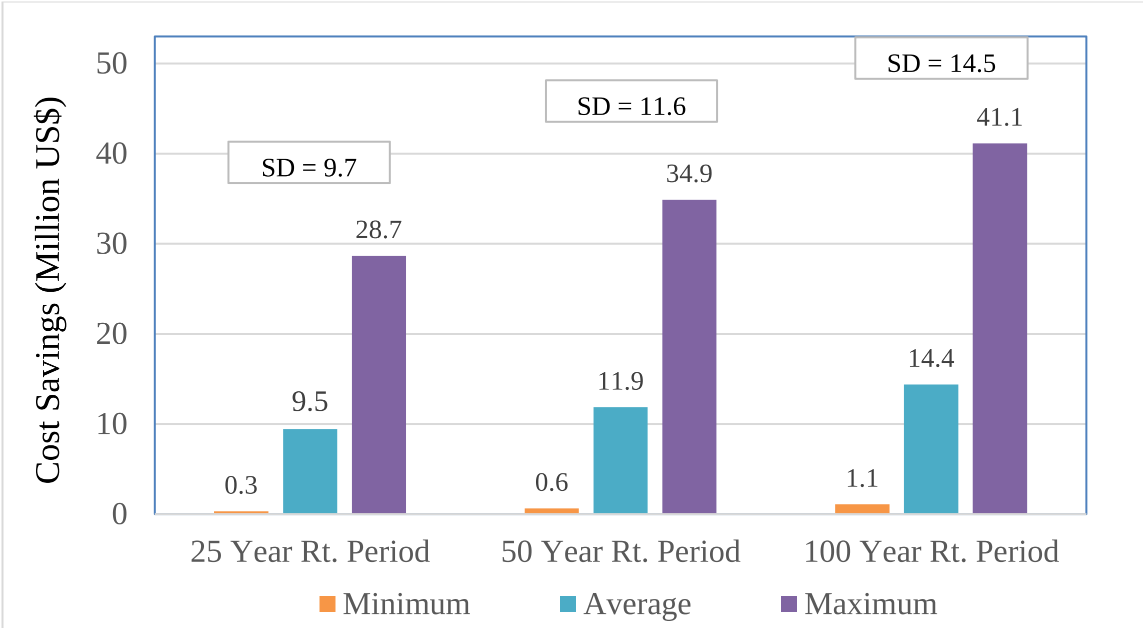


Figure 5.35: Cost savings with standard deviation (SD) by replacing desalinated water using runoff from Jizan (Cost savings are estimated for a single event of rainfall)

5.1.4.2 Carbon Emission Reduction

Water supply in Jizan is supplemented by the desalinated water from Al-Shuqaiq desalination plant (2nd phase) in the coast of the Red Sea [28]. Approximately, 7.4 MCM of desalinated water is supplied to Jizan in a year [28]. The Al-Shuqaiq (2nd phase) plant is operated by both RO and other distillation processes [77]. On average, emission of CO_2 from desalinated water can be approximated to be 34.8 (= 7.4 million $m^3 \times$ 4.7 kg/m^3) million kg per year (assuming RO is dominant).

The average runoff per event from the 25, 50 and 100 years' rainfall events were estimated to be 6.6, 5.6 and 10.6 MCM respectively and the corresponding ranges were 0.5 – 16.6, 1.0 – 20.2 and 1.6 – 23.8 MCM respectively (Figure **5.34**). Replacement of equivalent amount of desalinated water by the surface runoff can reduce CO_2 emissions significantly (Appendix: Table B.**8**). For the return periods of 25, 50 and 100 years, the average CO_2 reductions per event are 37.2, 46.7 and 56.6 million kg respectively with the ranges of 1.6 – 99.7, 3.4 – 121.3 and 5.5 – 143.0 million kg respectively (Figure **5.36**).

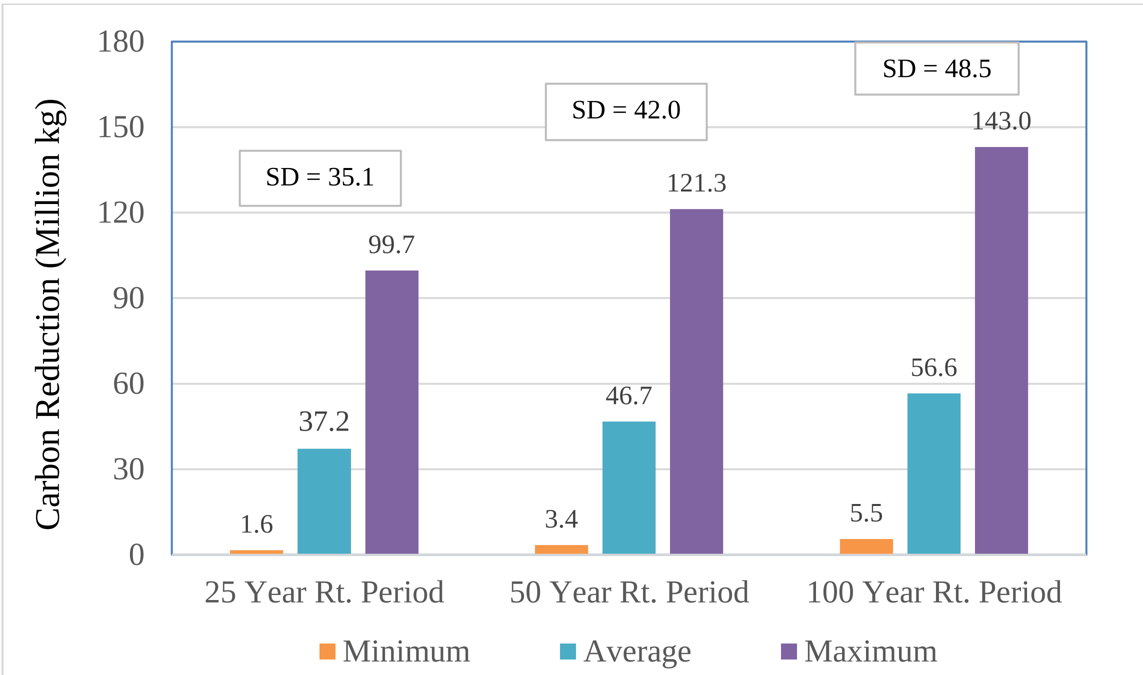


Figure 5.36: CO_2 reductions with standard deviation (SD) by replacing desalinated water using runoff from Jizan (CO_2 reductions are estimated for a single event of rainfall)

5.1.5 Khamis Mushait

For 25-year return period and the low rainfall event (49.6 mm), the runoff per event was estimated in the range of 0.1 – 3.1 MCM, with an average of 1.3 MCM. For the most likely rainfall event (62 mm), this range was 0.2 – 4.7 MCM, with an average of 2.2 MCM. For the high rainfall (74.4 mm), the runoff was estimated in the range of 0.6 – 6.5 MCM, with an average of 3.3 MCM (Figure **5.37**).

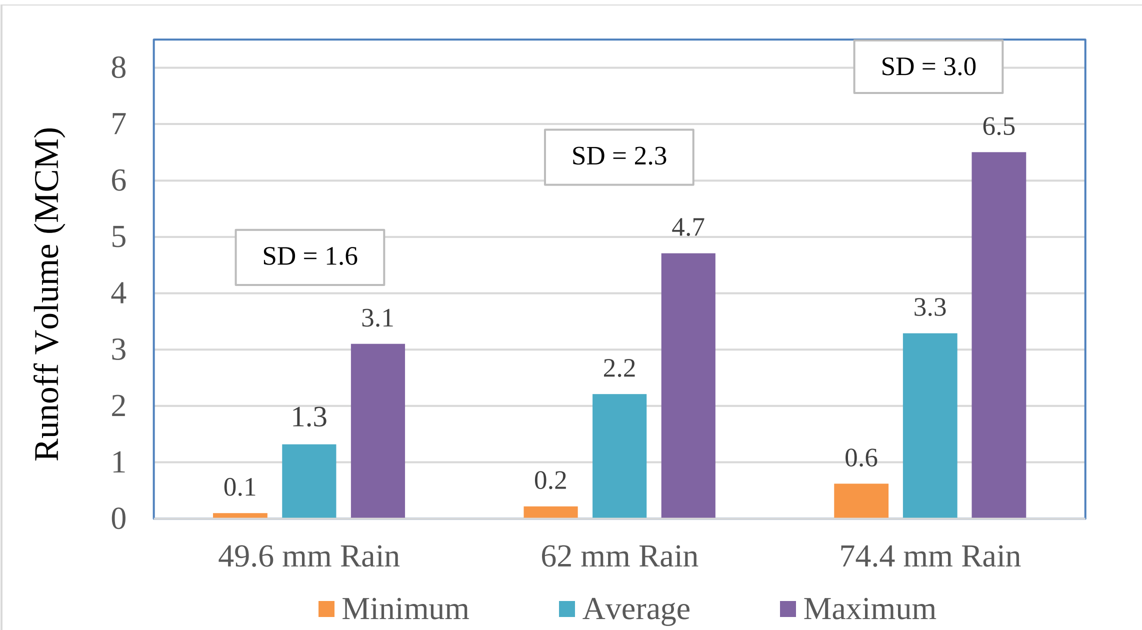


Figure 5.37: Variation of runoff volume with standard deviation (SD) for different rainfall depths in Khamis Mushait basin (Runoff are estimated for a single event of rainfall, for 25-year return period)

For the CN values of 53, 68 and 83, average runoff volumes per event were 0.3, 1.8 and 4.8 MCM and their corresponding ranges were 0.1 – 0.6, 0.8– 2.8 and 3.1 – 6.5 MCM respectively (Figure **5.38**).

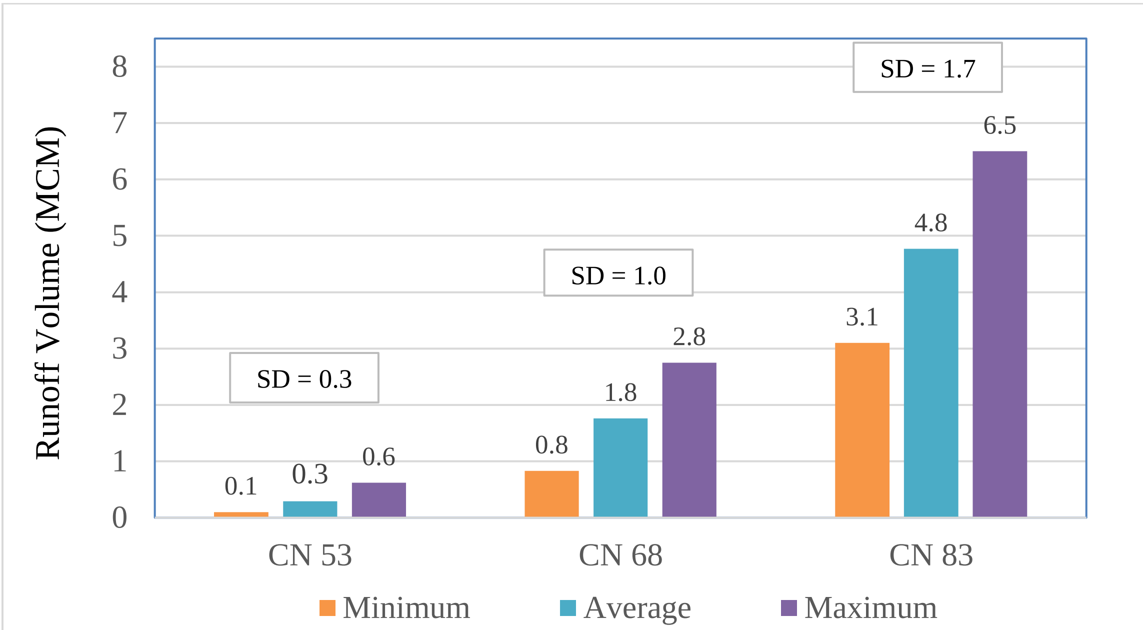


Figure 5.38: Variation of runoff volume with standard deviation (SD) for different curve numbers in Khamis Mushait basin (Runoff are estimated for a single event of rainfall, for 25-year return period)

For 50-year return period and the low rainfall event (57.1 mm), the runoff per event was estimated in the range of 0.1 – 4.1 MCM, with an average of 1.8 MCM. For the most likely rainfall event (71.4 mm), this range was 0.5 – 6.0 MCM, with an average of 3.0 MCM. For the high rainfall (85.7 mm), the runoff was estimated in the range of 1.1 – 8.2 MCM, with an average of 4.4 MCM (Figure **5.39**).

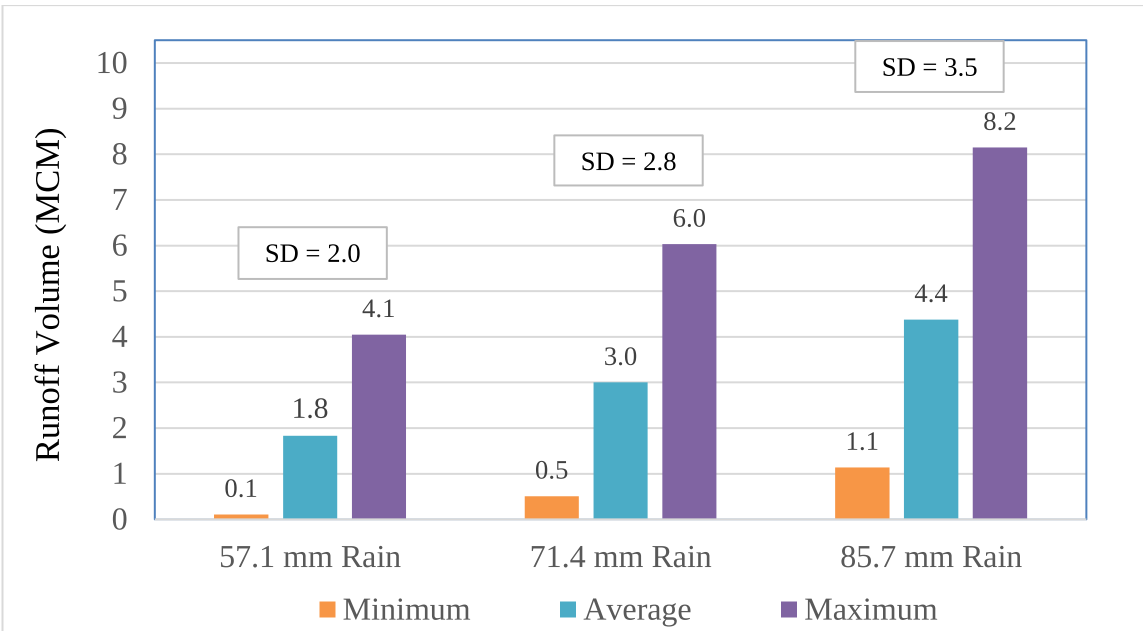


Figure 5.39: Variation of runoff volume with standard deviation (SD) for different rainfall depths in Khamis Mushait basin (Runoff are estimated for a single event of rainfall, for 50-year return period)

For the CN values of 53, 68 and 83, average runoff volumes per event were 0.6, 2.5 and 6.1 MCM and their corresponding ranges were 0.1 – 1.1, 1.3– 3.9 and 4.1 – 8.2 MCM respectively (Figure **5.40**).

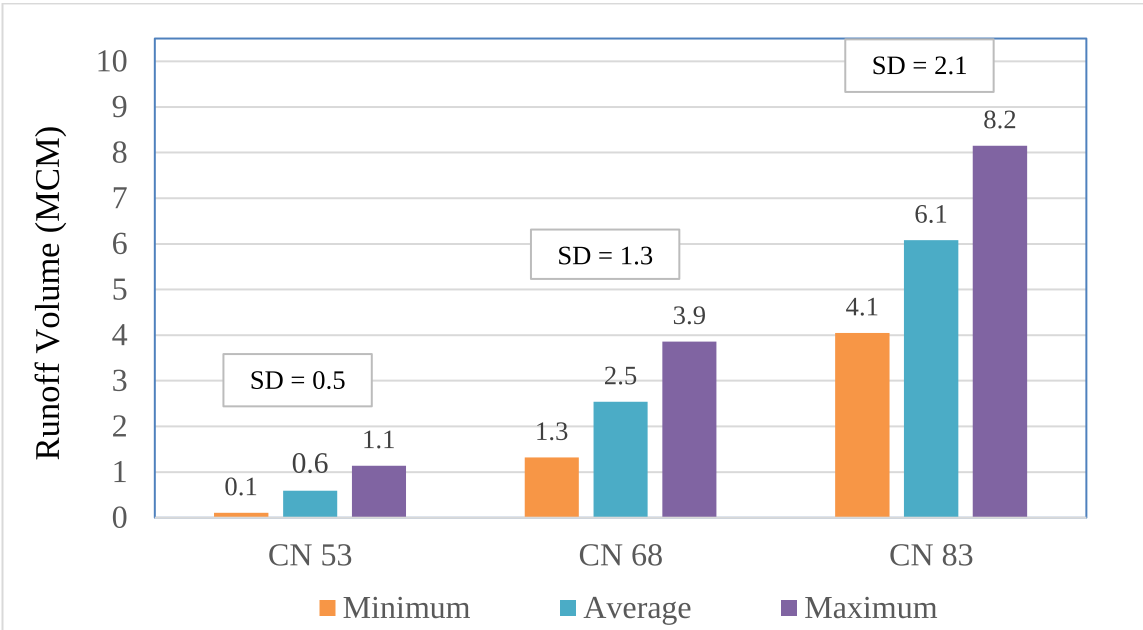


Figure 5.40: Variation of runoff volume with standard deviation (SD) for different curve numbers in Khamis Mushait basin (Runoff are estimated for a single event of rainfall, for 50-year return period)

For 100-year return period and the low rainfall event (64.5 mm), the runoff per event was estimated in the range of 0.3 – 5.0 MCM, with an average of 2.4 MCM. For the most likely rainfall event (80.6 mm), this range was 0.9 – 7.4 MCM, with an average of 3.9 MCM. For the high rainfall (96.7 mm), the runoff was estimated in the range of 1.8 – 9.9 MCM, with an average of 5.6 MCM (Figure **5.41**).

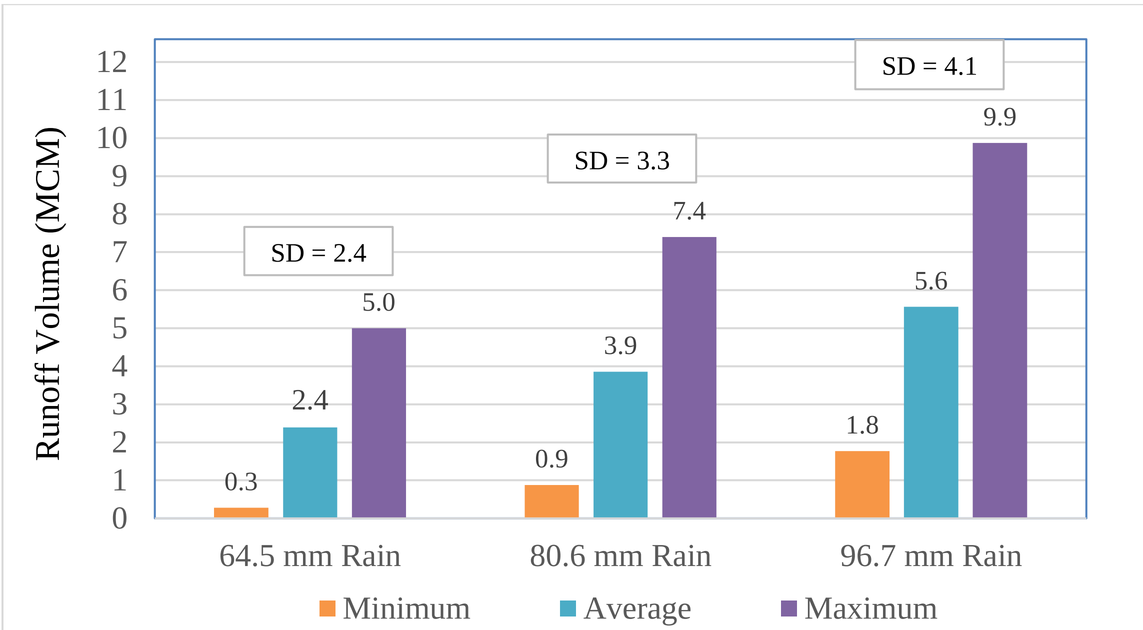


Figure 5.41: Variation of runoff volume with standard deviation (SD) for different rainfall depths in Khamis Mushait basin (Runoff are estimated for a single event of rainfall, for 100-year return period)

For the CN values of 53, 68 and 83, average runoff volumes per event were 1.0, 3.4 and 7.4 MCM and their corresponding ranges were 0.3 – 1.8, 1.9 – 5.1 and 5.0 – 9.9 MCM respectively (Figure **5.42**).

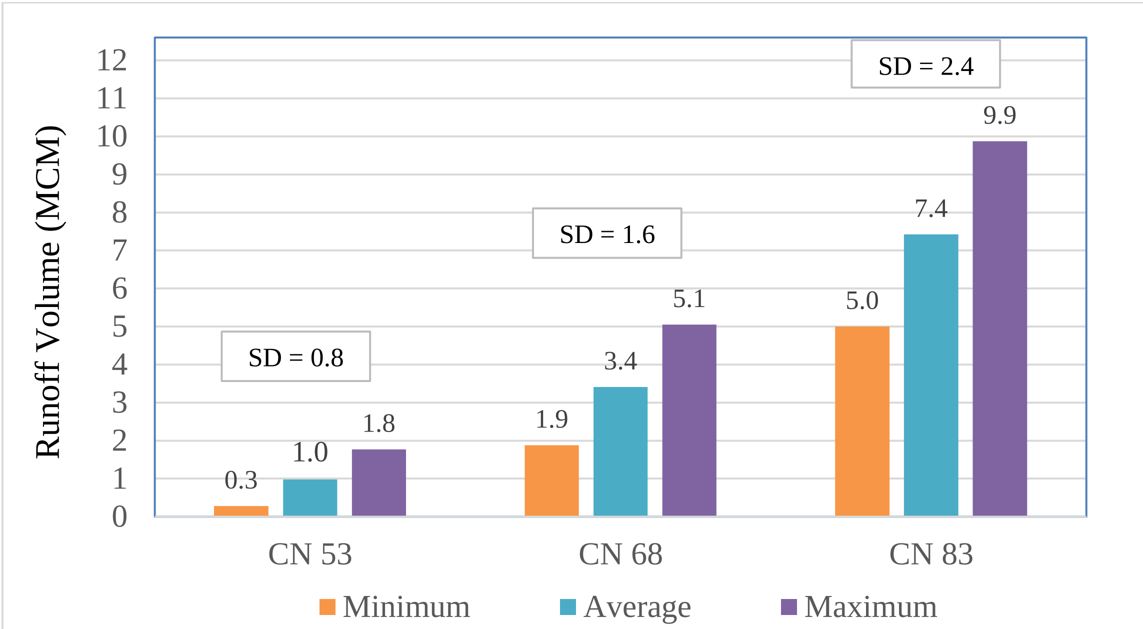


Figure 5.42: Variation of runoff volume with standard deviation (SD) for different curve numbers in Khamis Mushait basin (Runoff are estimated for a single event of rainfall, for 100-year return period)

Variation of runoff per event for different return periods is presented in Figure **5.43**. The averages of runoff in 9 scenarios for 25, 50 and 100-year rainfall events were 2.3, 3.1 and 3.9 MCM respectively while the corresponding ranges were 0.1 – 6.5, 0.1 – 8.2 and 0.3 – 9.9 MCM respectively.

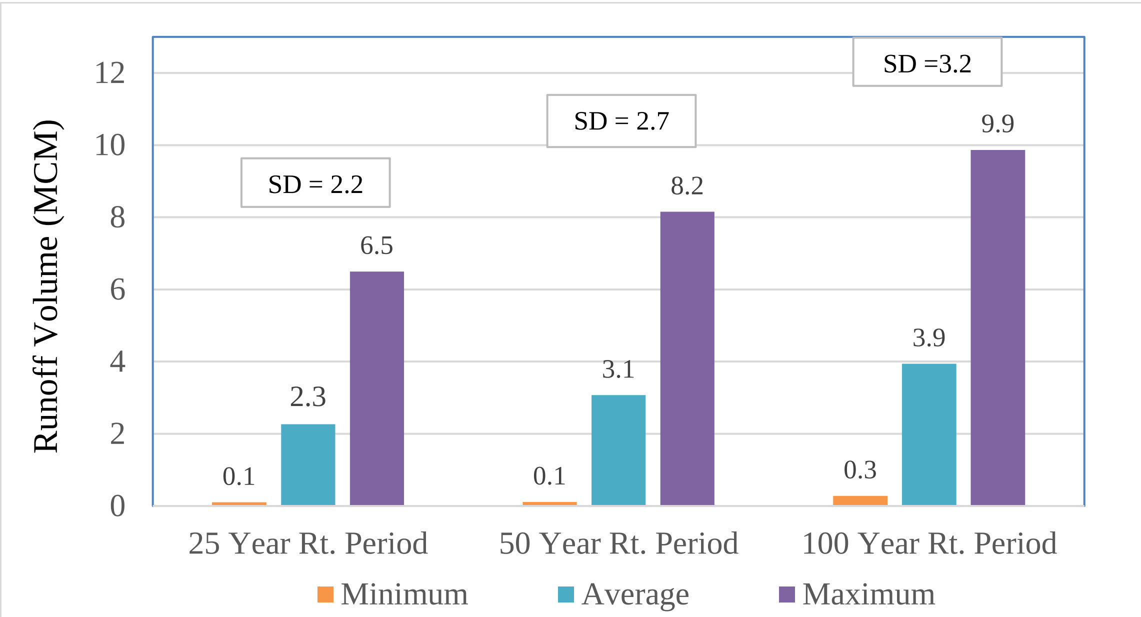


Figure 5.43: Variation of runoff volume with standard deviation (SD) for different return periods in Khamis Mushait (Runoff are estimated for a single event of rainfall)

5.1.5.1 Cost Saving

Replacement of equivalent amount of desalinated water by the surface runoff can save significant amounts of cost. The details are shown in Table B.**9** (Appendix B). For 25, 50 and 100 years' return periods, the average cost savings per event are US$ 3.3, 4.2 and 5.2 million with the ranges of US$ 0.1 – 10.6, 0.1 – 13.3 and 0.2 – 16.1 million respectively (Figure **5.44**).

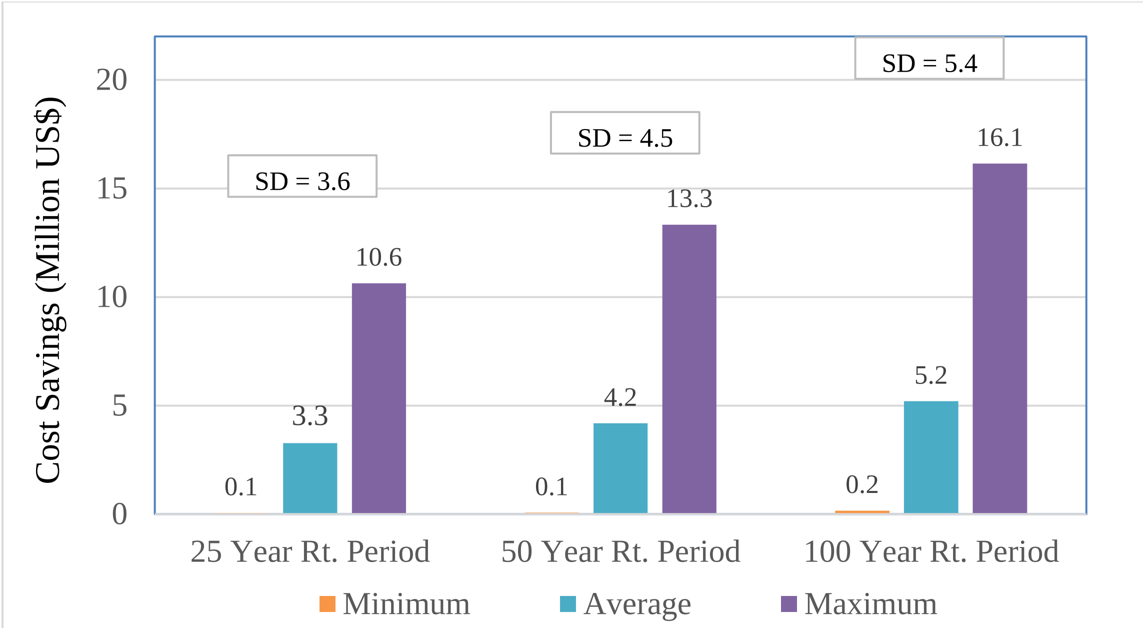


Figure 5.44: Cost savings with standard deviation (SD) by replacing desalinated water using runoff from Khamis Mushait (Cost savings are estimated for a single event of rainfall)

5.1.5.2 Carbon Emission Reduction

Water supply in Khamis Mushait is supplemented by the desalinated water from Al-Shuqaiq desalination plant in the coast of the Red Sea [88]. Approximately, 28.5 MCM of desalinated water is supplied to Khamis Mushait in a year [28]. The Al-Shuqaiq plant is operated by MSF distillation process that cogenerates electricity [77]. On average, emission of CO_2 from desalinated water can be approximated to be 420.4 (= 28.5 million $m^3 \times$ 14.8 kg/m^3) million kg per year.

The average runoff per event from the 25, 50 and 100 years' rainfall events were estimated to be 2.3, 3.1 and 3.9 MCM respectively and the corresponding ranges were 0.1

– 6.5, 0.1 – 8.2 and 0.3 – 9.9 MCM respectively (Figure **5.43**). Replacement of equivalent amount of desalinated water by the surface runoff can reduce CO_2 emissions significantly (Appendix: Table B.**10**). For the return periods of 25, 50 and 100 years, the average CO_2 reductions per event are 43.6, 55.7 and 69.3 million kg respectively with the ranges of 1.4 – 101.4, 1.5 – 127.1 and 3.9 – 154.0 million kg respectively (Figure **5.45**).

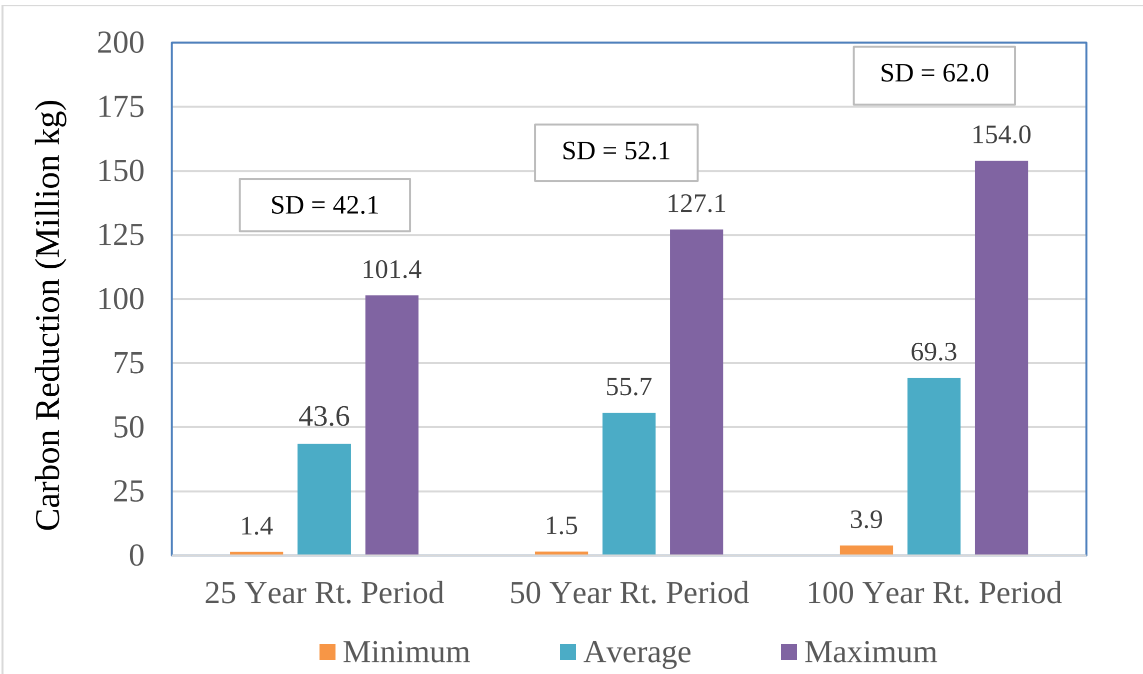


Figure 5.45: CO_2 reductions with standard deviation (SD) by replacing desalinated water using runoff from Khamis Mushait (CO_2 reductions are estimated for a single event of rainfall)

5.2 Summary

5.2.1 Runoff

The minimum, maximum and the average of runoff volume per event for different return periods are presented in Figure **5.46** -Figure **5.48**.

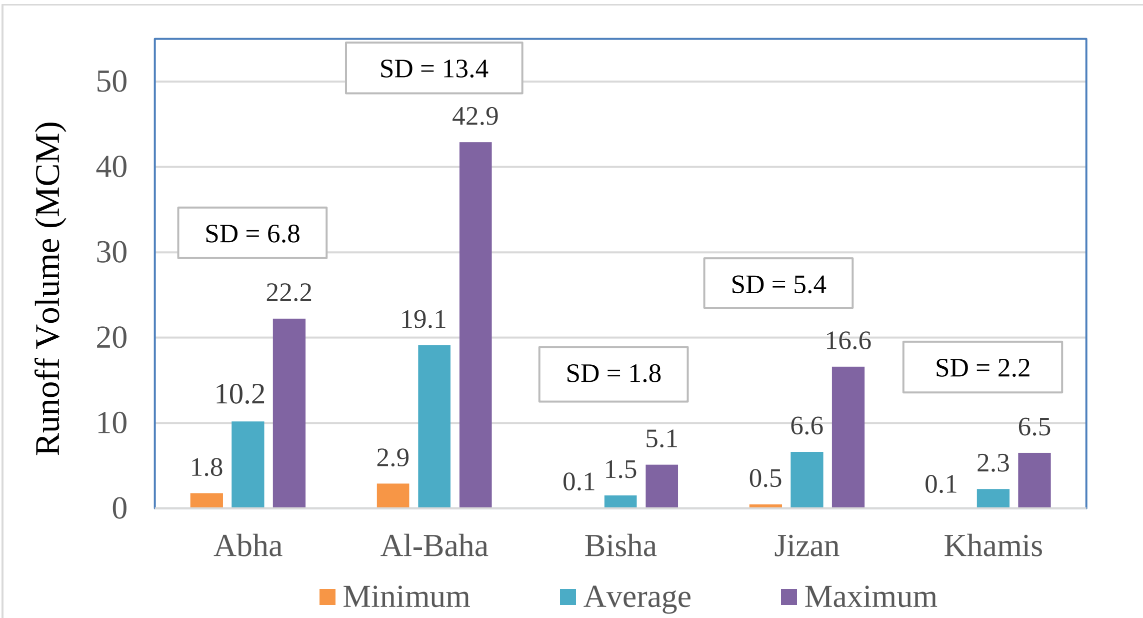


Figure 5.46: Variation of runoff volume with standard deviation (SD) for 25-year return period in different study areas (Runoff are estimated for a single event of rainfall)

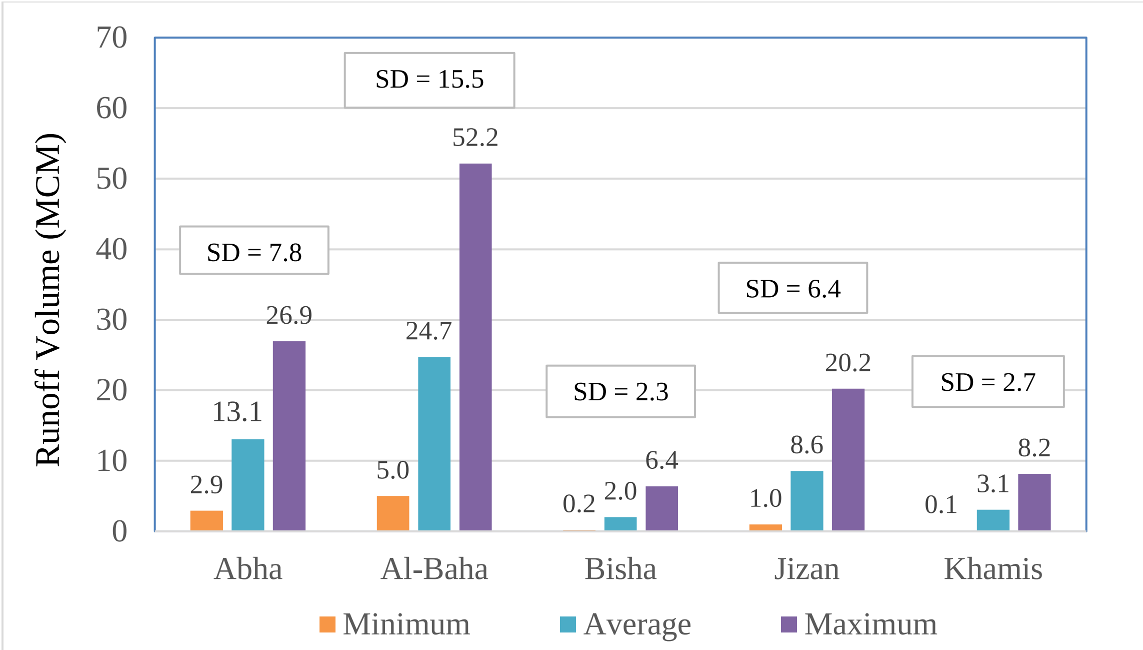


Figure 5.47: Variation of runoff volume with standard deviation (SD) for 50-year return period in different study areas (Runoff are estimated for a single event of rainfall)

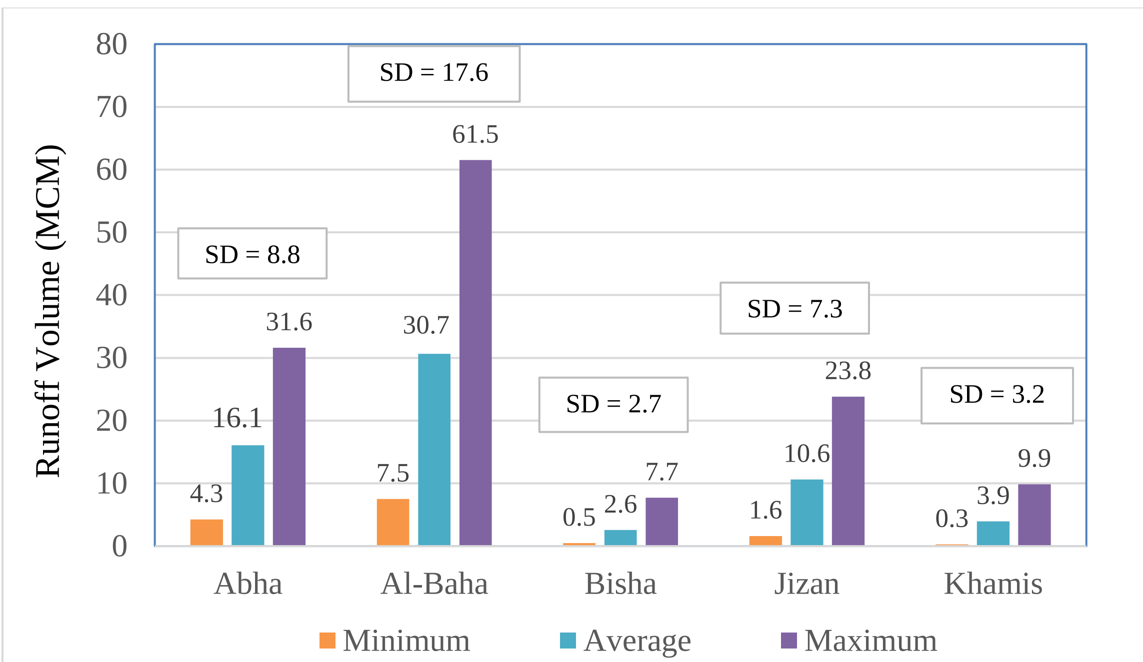


Figure 5.48: Variation of runoff volume with standard deviation (SD) for 100-year return period in different areas (Runoff are estimated for a single event of rainfall)

The runoff for single event of rainfall were later converted to runoff for single year, multiplying by the yearly event number from Table **3.3**, presented in Table **5.1**.

Table 5.1: Average runoff volume (million cubic meter) per year for the storms with different return periods

Area name	25-year return period	50-year return period	100-year return period
Abha	25.4	28.1	30.4
Al-Baha	35.2	39.0	42.2
Bisha	3.7	4.3	4.9
Jizan	13.1	14.9	16.4
Khamis Mushait	7.1	8.3	9.4

The runoff volumes were characterized by the statistical distributions. Runoff in Abha followed Normal and Loglogistic distributions for 25, 50 and 100-years return periods respectively (Figure C.6 - Figure C.8). For the same return period, runoff in Al-Baha and Bisha followed Weibull and 3-Parameter Weibull distributions; runoff in Jizan followed 3-Parameter Weibull and Normal distributions and Khamis Mushait followed 3-Parameter Weibull distribution (Figure C.9 - Figure C.20). Table **5.2** represents the runoff distributions in the study areas with their parameter values.

Table 5.2: Runoff distributions with parameter values

Area name	Return period	Distribution	Goodness of fit test
Abha	25-year	Normal (10.18, 6.75)	AD = 0.249, p-value = 0.656
	50-year	Loglogistic (2.424, 0.3894)	AD = 0.197, p-value > 0.250
	100-year	Loglogistic (2.66, 0.3488)	AD = 0.172, p-value > 0.250
Al-Baha	25-year	Weibull (1.529, 21.22)	AD = 0.174, p-value > 0.250
	50-year	Weibull (2.525, 38.52, -9.332)	AD = 0.207, p-value > 0.5
	100-year	Weibull (1.377, 26.73, 6.051)	AD = 0.201, p-value > 0.5
Bisha	25-year	Weibull (0.8202, 1.465, -0.112)	AD = 0.318, p-value > 0.5
	50-year	Weibull (1, 2.269, -0.2522)	AD = 0.267, p-value > 0.5
	100-year	Weibull (1.194, 3.258, -0.4874)	AD = 0.233, p-value > 0.5
Jizan	25-year	Weibull (1.84, 10.0, -2.212)	AD = 0.206, p-value > 0.5
	50-year	Weibull (2.102, 13.37, -3.201)	AD = 0.212, p-value > 0.5
	100-year	Normal (10.64, 7.306)	AD = 0.246, p-value = 0.665
Khamis Mushait	25-year	Weibull (1.414, 3.156, -0.5876)	AD = 0.218, p-value > 0.5
	50-year	Weibull (1.682, 4.58, -0.9977)	AD = 0.215, p-value > 0.5
	100-year	Weibull (1.889, 6.042, -1.396)	AD = 0.290, p-value > 0.5

5.2.2 Cost Saving

The cost savings for five watersheds and for different return periods by replacing equivalent desalinated water are presented in Figure **5.49** - Figure **5.51**.

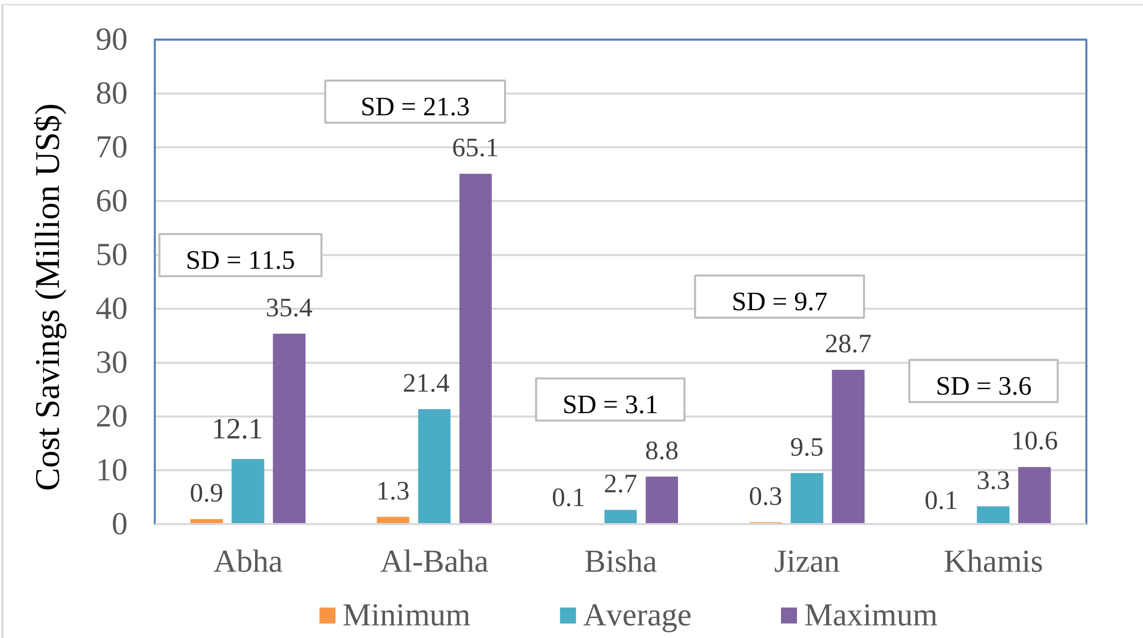


Figure 5.49: Variation of cost savings with standard deviation (SD) for 25-year return period in different study areas (Cost savings are estimated for a single event of rainfall)

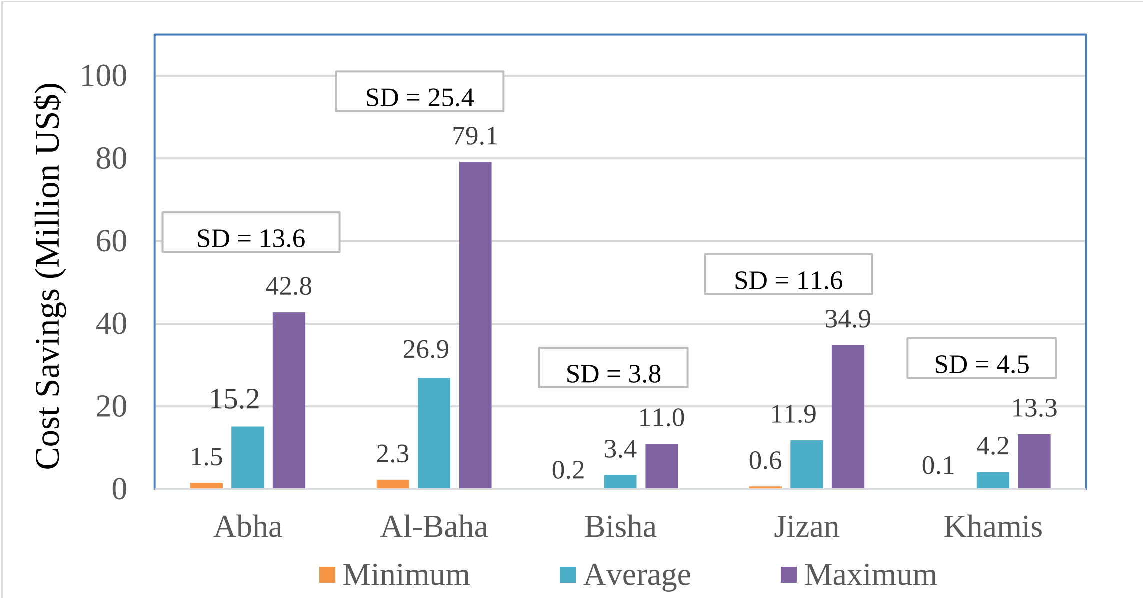


Figure 5.50: Variation of cost savings with standard deviation (SD) for 50-year return period in different study areas (Cost savings are estimated for a single event of rainfall)

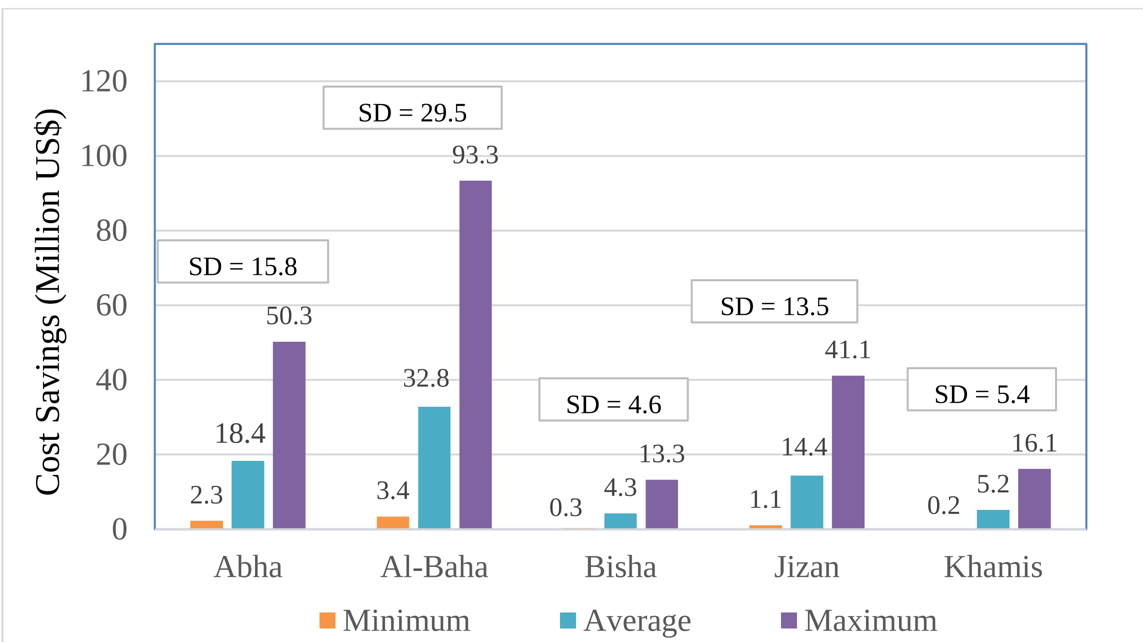


Figure 5.51: Variation of cost savings with standard deviation (SD) for 100-year return period in different study areas (Cost savings are estimated for a single event of rainfall)

5.2.3 Carbon Emission Reduction

The CO_2 emission reductions for five watersheds and for different return periods by replacing equivalent desalinated water are presented in Figure **5.52** - Figure **5.54**.

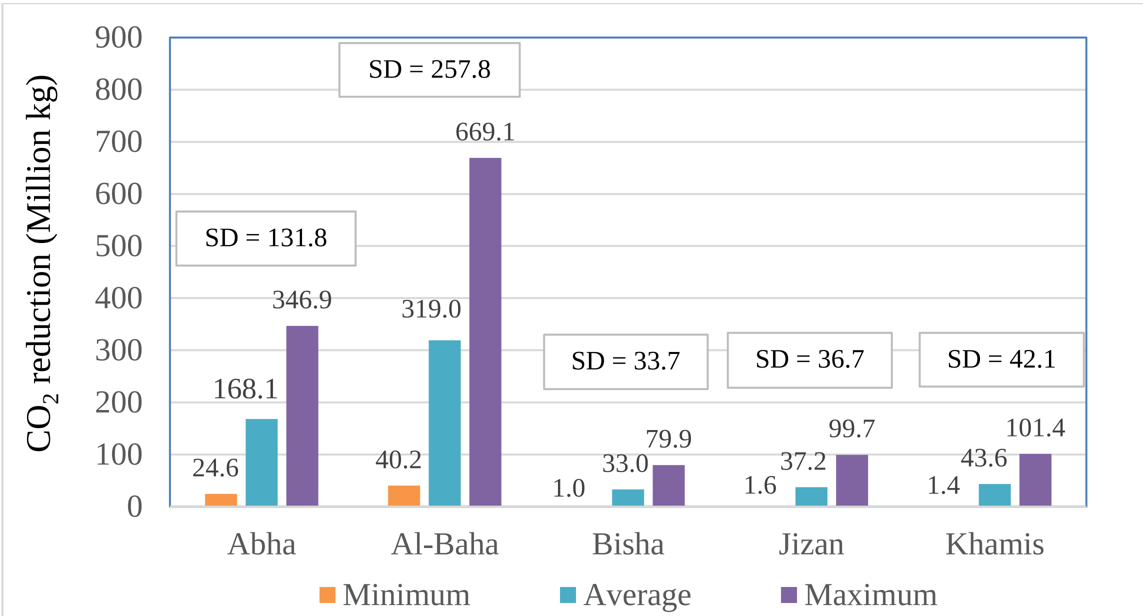


Figure 5.52: Variation of carbon emission reductions with standard deviation (SD) through replacing desalinated water by runoff water for 25-year return period in different study areas (CO_2 reductions are estimated for a single event of rainfall)

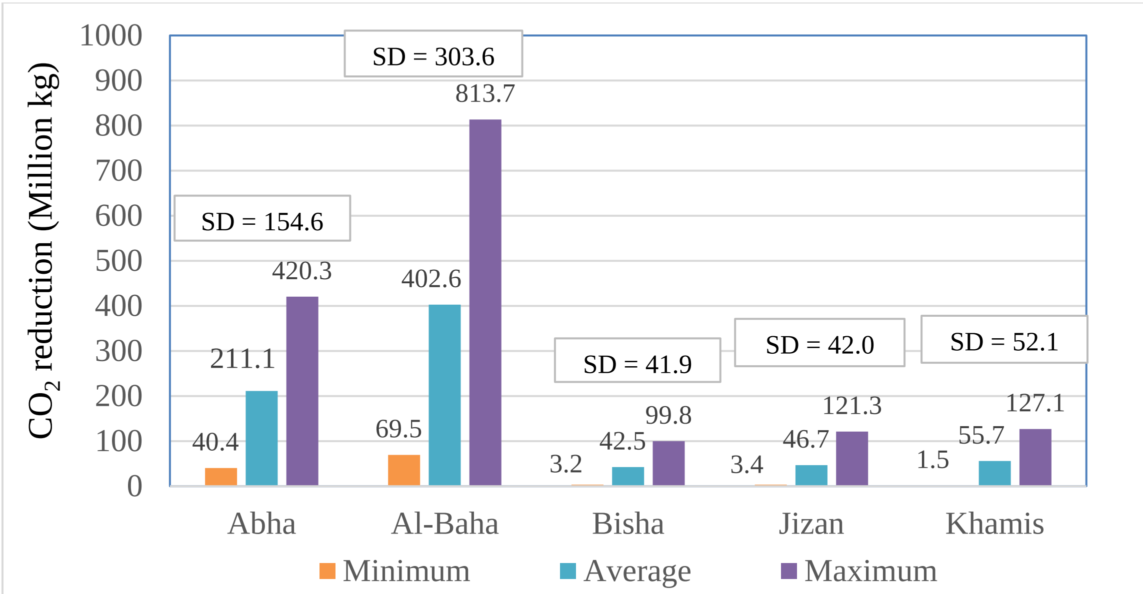


Figure 5.53: Variation of carbon emission reductions with standard deviation (SD) through replacing desalinated water by runoff water for 50-year return period in different study areas (CO_2 reductions are estimated for a single event of rainfall)

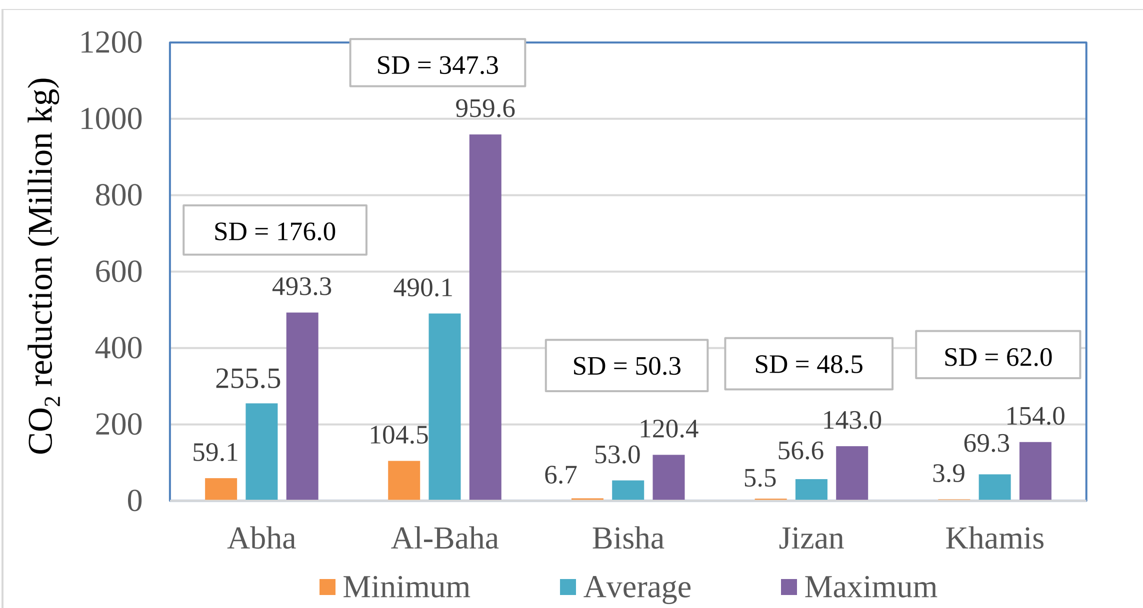


Figure 5.54: Variation of carbon emission reductions with standard deviation (SD) through replacing desalinated water by runoff water for 100-year return period in different study areas (CO_2 reductions are estimated for a single event of rainfall)

5.3 Discussion

A total of 9 different scenarios of runoff collection were analyzed for each study area. In Abha, the average runoff volumes were 10.2, 13.1 and 16.1 MCM per event for the storm of 25, 50 and 100-years return periods respectively (Figure **5.46** - Figure **5.48**). For the same return periods, the average volume of runoff per year were estimated to be 25.4, 28.1 and 30.4 MCM respectively (multiplying by the yearly event number from Table **3.3**). The storage capacity for the suggested dam in Abha was 1.3 MCM (Table **4.7**), which is much lower than the potential runoff volume. Consequently, there prevails the risk of flooding and possibility of loss of runoff. To exploit the maximum amount of runoff, the watershed can be excavated and/or the flow can be diverted through creating artificial channel. Future study is warranted in this context.

The runoff in Al-Baha was estimated to be the largest among the five study areas, due mainly to the largest catchment area. The averages of runoff in Al-Baha for the storm of 25, 50 and 100-years return periods were 19.1, 24.7 and 30.7 MCM per event and 35.2, 39.0 and 42.2 MCM per year respectively. While, the reservoir capacity for the suggested dam was 4.7 MCM, which is lower than the average runoff generation per storm event. Diversion of runoff-excess and/or excavation prior to the dam location can assist in increasing the capacity of the dam.

Among the five study areas, Bisha had the minimum runoff, due mainly to the low rainfall. The average of runoff in Bisha for 100-years return period was 2.6 MCM per event and 4.9 MCM per year. While the reservoir capacity in Bisha was 23.8 MCM, which is much higher than the average yearly runoff volume.

The averages of runoff in Jizan for 25, 50 and 100-years return periods were 6.6, 8.6 and 10.6 MCM per event and 13.1, 14.9 and 16.4 MCM per year respectively. While, the reservoir capacity for the suggested dam was only 0.8 MCM. Moreover, the most suitable location for dam construction was situated in a relatively plane area. The depth of the outlet location from the bank was only 3 meters, indicating that construction of a concrete structure may not be feasible. An earthen embankment of low height can be constructed in the selected location to facilitate the recharge the runoff.

The runoff volumes in Khamis Mushait were lower than the runoff in Abha, Al-Baha and Jizan, due mainly to its low watershed area and low CN value. The averages of runoff in Khamis Mushait for 25, 50 and 100-years return periods were 2.3, 3.1 and 3.9 MCM per event and 7.1, 8.3 and 9.4 MCM per year respectively. The reservoir capacity for the suggested dam was 4.6 MCM, which is higher than the runoff generation per storm event.

In Bisha, Jizan and Khamis Mushait, there is a chance of generating minimal runoff (in the case of runoff for minimum CN and minimum rainfall depth). In other cases, noticeable runoff might be generated in all locations. The runoff collected in the reservoirs can be artificially injected to aquifer to make space for the runoff from subsequent rainfall event. In Abha and Al-Baha, the excess runoff might be shifted into downstream areas using diversion head works or constructing additional dams. Among the estimated cost and carbon savings in replacing desalinated water by runoff, Al-Baha had the maximum savings and Bisha had the minimum savings. It is to be noted that construction of dams over the wadi can be expensive with costs in the ranges of US$ 0.3 – over 1 billion [37]. Future study should focus on the feasibility of large dams or the small ponding locations of with immediate recharge capabilities.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

Saudi Arabia is an arid country with limited amount of renewable water resources. Excessive use of groundwater is snatching the country towards an ominous situation. Surface runoff generated from heavy rainfall can contribute to the national fresh water resources to some extent. The exploitation of the surface runoff will alleviate the pressure from the desalinated water use, which will help the country in saving money and the environment as well. In this goal, the present study identifies the locations of five new dams in five areas (Abha, Al-Baha, Bisha, Jizan and Khamis Mushait) of the southwestern region of Saudi Arabia. The potential runoff collected by the new dams were estimated for different return periods. The cost saving and the carbon emission reduction from replacing the equivalent amount of desalinated water by the runoff was calculated later. The following conclusions are drawn from the study:

1. For the return period of 25, 50 and 100 years, the yearly average runoff were estimated to be in the ranges of 25.4 – 30.4, 35.2 – 42.2, 3.7 – 4.9, 13.1 – 16.4 and 7.1 – 9.4 MCM for Abha, Al-Baha, Bisha, Jizan and Khamis Mushait respectively. The runoff volumes were found to be sensitive to the rainfall depths and CN values. The higher rainfall depth and higher CN produced higher runoff while the reverse is true for lower rainfall depth and lower CN. Appropriate use of

this water can reduce the cost in comparison to using desalinated water while it will reduce carbon emission into the environment.

2. Use of the runoff for domestic purposes can save US$ 30.1 – 34.6, 39.4 – 45.2, 6.4 – 7.8, 18.7 – 22.2 and 10.1 – 12.4 million per year for Abha, Al-Baha, Bisha, Jazan and Khamis Mushait respectively. The corresponding averages of cost savings are US$ 32.5, 42.5, 7.2, 20.6 and 11.3 million per year respectively.
3. This replacement will reduce CO_2 emission in the ranges of 419.3 – 481.8, 588.1 – 674.5, 79.6 – 96.7, 73.5 – 87.1 and 134.5 – 165.9 million kg per year in Abha, Al-Baha, Bisha, Jazan and Khamis Mushait respectively. The corresponding averages of CO_2 emission reductions are 452.9, 634.5, 88.7, 80.8 and 150.6 million kg per year respectively.

The present study identifies the tentative locations of five new dams in five areas. However, the cost of dam construction, technical and economic feasibility, and environmental impact of new dams need better understanding. In addition, the surface evaporation can be a significant factor in the hot dry areas, such as, Saudi Arabia. This study recommends the following research for better management of the water resources in the country:

1. Identify the exact locations of the dams using the field survey.
2. Study the feasibility for the large open surface dam vs. small ponds followed by artificial recharge of the aquifer.

3. Develop the National database for soil type, land use pattern and the Curve Number.
4. Conduct the Environmental Impact Assessment (EIA) study of new dams in southwest region of Saudi Arabia.

APPENDIX-A: Runoff Volumes in Five Study Areas for Varying CN and Rainfall Depth

Table A.1: Runoff volume per event in Abha basin for varying CN and rainfall depth (for 25-year return period)

No. of result	CN	Rainfall depth (mm)	Runoff volume (MCM)
1	60	69.0	1.8
2	60	86.2	3.6
3	75	69.0	5.8
4	60	103.4	5.9
5	75	86.2	9.1
6	75	103.4	12.8
7	90	69.0	12.8
8	90	86.2	17.5
9	90	103.4	22.2
		Minimum	1.8
		Average	10.2
		Maximum	22.2
		Standard deviation	6.8

Table A.2: Runoff volume per event in Abha basin for varying CN and rainfall depth (for 50-year return period)

No. of result	CN	Rainfall depth (mm)	Runoff volume (MCM)
1	60	80.7	2.9
2	60	100.2	5.5
3	75	80.7	7.9
4	60	120.2	8.6
5	75	100.2	12.1
6	90	80.7	15.8
7	75	120.2	16.6
8	90	100.2	21.3
9	90	120.2	26.9
		Minimum	2.9
		Most likely	13.1
		Maximum	26.9
		Standard deviation	7.8

Table A.3: Runoff volume per event in Abha basin for varying CN and rainfall depth (for 100-year return period)

No. of result	CN	Rainfall depth (mm)	Runoff volume (MCM)
1	60	91.2	4.3
2	60	114	7.5
3	75	91.2	10.2
4	60	136.8	11.4
5	75	114	15.2
6	90	91.2	18.9
7	75	136.8	20.6
8	90	114	25.2
9	90	136.8	31.6
		Minimum	4.3
		Most likely	16.1
		Maximum	31.6
		Standard deviation	8.8

Table A.4: Runoff volume per event in Al-Baha basin for varying CN and rainfall depth, for 25-year return period

No. of result	CN	Rainfall depth (mm)	Runoff volume (MCM)
1	62	60.3	2.9
2	62	75.4	6.1
3	62	90.5	10.3
4	77	60.3	10.6
5	77	75.4	16.7
6	77	90.5	23.5
7	92	60.3	25.1
8	92	75.4	33.9
9	92	90.5	42.9
		Minimum	2.9
		Most likely	19.1
		Maximum	42.9
		Standard deviation	13.4

Table A.5: Runoff volume per event in Al-Baha basin for varying CN and rainfall depth, for 50-year return period

No. of result	CN	Rainfall depth (mm)	Runoff volume (MCM)
1	62	70.6	5.0
2	62	88.2	9.6
3	77	70.6	14.6
4	62	105.8	15.2
5	77	88.2	22.4
6	77	105.8	30.9
7	92	70.6	31.1
8	92	88.2	41.5
9	92	105.8	52.2
		Minimum	5.0
		Most likely	24.7
		Maximum	52.2
		Standard deviation	15.5

Table A.6: Runoff volume per event in Al-Baha basin for varying CN and rainfall depth, for 100-year return period

No. of result	CN	Rainfall depth (mm)	Runoff volume (MCM)
1	62	80.8	7.5
2	62	101	13.6
3	77	80.8	19.1
4	62	121.2	20.7
5	77	101	28.5
6	92	80.8	37.1
7	77	121.2	38.7
8	92	101	49.2
9	92	121.2	61.5
		Minimum	7.5
		Most likely	30.7
		Maximum	61.5
		Standard deviation	17.6

Table A.7: Runoff volume per event in Bisha basin for varying CN and rainfall depth, for 25-year return period

No. of result	CN	Rainfall depth (mm)	Runoff volume (MCM)
1	58	29.1	0.1
2	58	36.4	0.1
3	58	43.7	0.1
4	73	29.1	0.3
5	73	36.4	0.8
6	73	43.7	1.4
7	88	29.1	2.4
8	88	36.4	3.7
9	88	43.7	5.1
		Minimum	0.1
		Most likely	1.5
		Maximum	5.1
		Standard deviation	1.8

Table A.8: Runoff volume per event in Bisha basin for varying CN and rainfall depth, for 50-year return period

No. of result	CN	Rainfall depth (mm)	Runoff volume (MCM)
1	58	33.1	0.2
2	58	41.4	0.2
3	58	49.7	0.2
4	73	33.1	0.5
5	73	41.4	1.2
6	73	49.7	2.1
7	88	33.1	3.1
8	88	41.4	4.7
9	88	49.7	6.4
		Minimum	0.2
		Most likely	2.0
		Maximum	6.4
		Standard deviation	2.3

Table A.9: Runoff volume per event in Bisha basin for varying CN and rainfall depth, for 100-year return period

No. of result	CN	Rainfall depth (mm)	Runoff volume (MCM)
1	58	37.1	0.5
2	58	46.4	0.5
3	58	55.7	0.5
4	73	37.1	0.8
5	73	46.4	1.7
6	73	55.7	2.8
7	88	37.1	3.8
8	88	46.4	5.7
9	88	55.7	7.7
		Minimum	0.5
		Most likely	2.6
		Maximum	7.7
		Standard deviation	2.7

Table A.10: Runoff volume per event in Jizan basin for varying CN and rainfall depth, for 25-year return period

No. of result	CN	Rainfall depth (mm)	Runoff volume (MCM)
1	57	55.8	0.5
2	57	69.8	1.4
3	57	83.8	2.8
4	72	55.8	3.2
5	72	69.8	5.5
6	72	83.8	8.2
7	87	55.8	8.8
8	87	69.8	12.6
9	87	83.8	16.6
		Minimum	0.5
		Most likely	6.6
		Maximum	16.6
		Standard deviation	5.4

Table A.11: Runoff volume per event in Jizan basin for varying CN and rainfall depth, for 50-year return period

No. of result	CN	Rainfall depth (mm)	Runoff volume (MCM)
1	57	63.7	1.0
2	57	79.6	2.4
3	57	95.5	4.3
4	72	63.7	4.5
5	72	79.6	7.4
6	72	95.5	10.8
7	87	63.7	11.0
8	87	79.6	15.5
9	87	95.5	20.2
		Minimum	1.0
		Most likely	8.6
		Maximum	20.2
		Standard deviation	6.4

Table A.12: Runoff volume per event in Jizan basin for varying CN and rainfall depth, for 100-year return period

No. of result	CN	Rainfall depth (mm)	Runoff volume (MCM)
1	57	71.7	1.6
2	57	89.6	3.6
3	72	71.7	5.9
4	57	107.5	6.0
5	72	89.6	9.5
6	87	71.7	13.3
7	72	107.5	13.6
8	87	89.6	18.5
9	87	107.5	23.8
		Minimum	1.6
		Most likely	10.6
		Maximum	23.8
		Standard deviation	7.3

Table A.13: Runoff volume per event in Khamis Mushait basin for varying CN and rainfall depth, for 25-year return period

No. of result	CN	Rainfall depth (mm)	Runoff volume (MCM)
1	53	49.6	0.1
2	53	62	0.2
3	53	74.4	0.6
4	68	49.6	0.8
5	68	62	1.7
6	68	74.4	2.8
7	83	49.6	3.1
8	83	62	4.7
9	83	74.4	6.5
		Minimum	0.1
		Most likely	2.3
		Maximum	6.5
		Standard deviation	2.2

Table A.14: Runoff volume per event in Khamis Mushait basin for varying CN and rainfall depth, for 50-year return period

No. of result	CN	Rainfall depth (mm)	Runoff volume (MCM)
1	53	57.1	0.1
2	53	71.4	0.5
3	53	85.7	1.1
4	68	57.1	1.3
5	68	71.4	2.5
6	68	85.7	3.9
7	83	57.1	4.1
8	83	71.4	6.0
9	83	85.7	8.2
		Minimum	0.1
		Most likely	3.1
		Maximum	8.2
		Standard deviation	2.7

Table A.15: Runoff volume per event in Khamis Mushait basin for varying CN and rainfall depth, for 100-year return period

No. of result	CN	Rainfall depth (mm)	Runoff volume (MCM)
1	53	64.5	0.3
2	68	64.5	1.9
3	83	64.5	5.0
4	53	80.6	0.9
5	68	80.6	3.3
6	83	80.6	7.4
7	53	96.7	1.8
8	68	96.7	5.1
9	83	96.7	9.9
		Minimum	0.3
		Most likely	3.9
		Maximum	9.9
		Standard deviation	3.2

APPENDIX-B: Cost Saving and Carbon Reduction

Table B.1: Cost saving per event by replacing desalinated water using runoff from Abha

No. of result	Cost saving (Million US$)		
	25-year Rt. period	50-year Rt. period	100-year Rt. period
1	0.9	1.5	2.3
2	11.8	14.3	16.7
3	5.4	6.9	8.5
4	2.8	4.6	6.8
5	35.4	42.8	50.3
6	16.2	20.8	25.6
7	1.9	3.1	4.5
8	23.6	28.5	33.5
9	10.8	13.9	17.1
Minimum	0.9	1.5	2.3
Most likely	12.1	15.2	18.4
Maximum	35.4	42.8	50.3
St. deviation	11.5	13.6	15.8

Table B.2: CO_2 reduction per event by replacing desalinated water using runoff from Abha

No. of result	CO_2 reduction (Million kg)		
	25-year Rt. period	50-year Rt. period	100-year Rt. period
1	24.6	40.5	59.1
2	309.1	374.5	439.5
3	141.5	181.8	223.7
4	27.6	45.4	66.3
5	346.9	420.3	493.3
6	158.8	204.1	251.0
7	26.1	42.9	62.7
8	328.0	397.4	466.4
9	150.2	192.9	237.3
Minimum	24.6	40.5	59.1
Most likely	168.1	211.1	255.5
Maximum	346.9	420.3	493.3
St. deviation	131.8	154.6	176.0

Table B.3: Cost saving per event by replacing desalinated water using runoff from Al-Baha

No. of result	Cost saving (Million US$)		
	25-year Rt. period	50-year Rt. period	100-year Rt. period
1	1.3	2.3	3.4
2	19.6	23.9	28.1
3	8.7	11.3	14.0
4	4.4	7.6	11.4
5	65.1	79.2	93.3
6	29.1	37.5	46.5
7	2.9	4.9	7.4
8	42.4	51.5	60.7
9	18.9	24.4	30.3
Minimum	1.3	2.3	3.4
Most likely	21.4	27.0	32.8
Maximum	65.1	79.2	93.3
St. deviation	21.3	25.4	29.5

Table B.4: CO_2 reduction per event by replacing desalinated water using runoff from Al-Baha

No. of result	CO_2 reduction (Million kg)		
	25-year Rt. period	50-year Rt. period	100-year Rt. period
1	40.2	69.5	104.5
2	596.2	725.0	855.0
3	265.5	343.6	426.0
4	45.1	78.0	117.3
5	669.1	813.7	959.6
6	298.0	385.6	478.1
7	42.6	73.8	110.9
8	632.6	769.4	907.3
9	281.7	364.6	452.1
Minimum	40.2	69.5	104.5
Most likely	319.0	402.6	490.1
Maximum	669.1	813.7	959.6
St. deviation	257.8	303.6	347.3

Table B.5: Cost saving per event by replacing desalinated water using runoff from Bisha

No. of result	Cost saving (Million US$)		
	25-year Rt. period	50-year Rt. period	100-year Rt. period
1	0.0	0.2	0.3
2	3.4	4.2	5.1
3	1.0	1.3	1.7
4	0.1	0.4	0.8
5	8.8	11.0	13.3
6	2.6	3.5	4.4
7	0.1	0.3	0.6
8	6.1	7.6	9.2
9	1.8	2.4	3.1
Minimum	0.1	0.2	0.3
Most likely	2.7	3.4	4.3
Maximum	8.8	11.0	13.3
St. deviation	3.0	3.7	4.4

Table B.6: CO_2 reduction per event by replacing desalinated water using runoff from Bisha

No. of result	CO_2 reduction (Million kg)		
	25-year Rt. period	50-year Rt. period	100-year Rt. period
1	1.0	3.2	6.7
2	71.2	89.0	107.3
3	21.1	28.1	35.7
4	1.1	3.6	7.5
5	79.9	99.8	120.4
6	23.7	31.5	40.1
7	1.0	3.4	7.1
8	75.5	94.4	113.9
9	22.4	29.8	37.9
Minimum	1.0	3.2	6.7
Most likely	33.0	42.5	53.0
Maximum	79.9	99.8	120.4
St. deviation	33.3	40.6	47.7

Table B.7: Cost saving per event by replacing desalinated water using runoff from Jizan

No. of result	Cost saving (Million US$)		
	25-year Rt. period	50-year Rt. period	100-year Rt. period
1	0.3	0.6	1.1
2	11.1	13.5	15.9
3	4.4	5.7	7.1
4	0.8	1.7	2.8
5	28.7	34.9	41.1
6	11.4	14.8	18.4
7	0.6	1.1	1.9
8	19.9	24.2	28.5
9	7.9	10.3	12.7
Minimum	0.3	0.6	1.1
Most likely	9.5	11.9	14.4
Maximum	28.7	34.9	41.1
St. deviation	9.7	11.6	13.5

Table B.8: CO_2 reduction per event by replacing desalinated water using runoff from Jizan

No. of result	CO_2 reduction (Million kg)		
	25-year Rt. period	50-year Rt. period	100-year Rt. period
1	1.6	3.4	5.5
2	56.5	68.7	81.1
3	22.5	29.2	36.2
4	2.9	6.0	9.8
5	99.7	121.3	143.0
6	39.8	51.5	63.8
7	2.3	4.7	7.7
8	78.1	95.0	112.0
9	31.2	40.3	50.0
Minimum	1.6	3.4	5.5
Most likely	37.2	46.7	56.6
Maximum	99.7	121.3	143.0
St. deviation	35.1	41.9	48.5

Table B.9: Cost saving per event by replacing desalinated water using runoff from Khamis Mushait

No. of result	Cost saving (Million US$)		
	25-year Rt. period	50-year Rt. period	100-year Rt. period
1	0.1	0.1	0.2
2	3.7	4.7	5.7
3	1.3	1.8	2.3
4	0.2	0.2	0.5
5	10.6	13.3	16.1
6	3.7	5.0	6.4
7	0.1	0.1	0.3
8	7.2	9.0	10.9
9	2.5	3.4	4.4
Minimum	0.1	0.1	0.2
Most likely	3.3	4.2	5.2
Maximum	10.6	13.3	16.1
St. deviation	3.6	4.5	5.4

Table B.10: CO_2 reduction per event by replacing desalinated water using runoff from Khamis Mushait

No. of result	CO_2 reduction (Million kg)		
	25-year Rt. period	50-year Rt. period	100-year Rt. period
1	1.4	1.5	3.9
2	90.4	113.3	137.2
3	31.6	42.7	54.8
4	1.6	1.7	4.4
5	101.4	127.1	154.0
6	35.4	47.9	61.5
7	1.5	1.6	4.1
8	95.9	120.2	145.6
9	33.5	45.3	58.1
Minimum	1.4	1.5	3.9
Most likely	43.6	55.7	69.3
Maximum	101.4	127.1	154.0
St. deviation	41.7	52.1	62.0

APPENDIX-C: Figures (Geological Maps and Runoff Distributions)

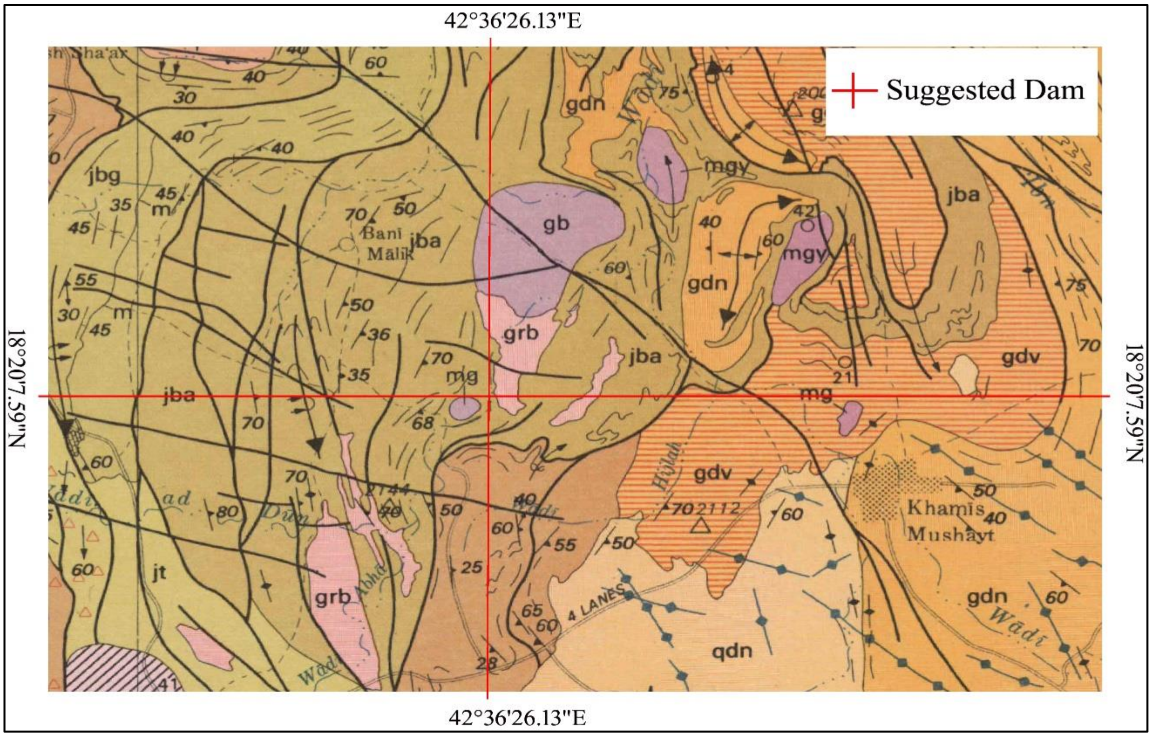


Figure C.1: Geological condition of suggested dam location in Abha

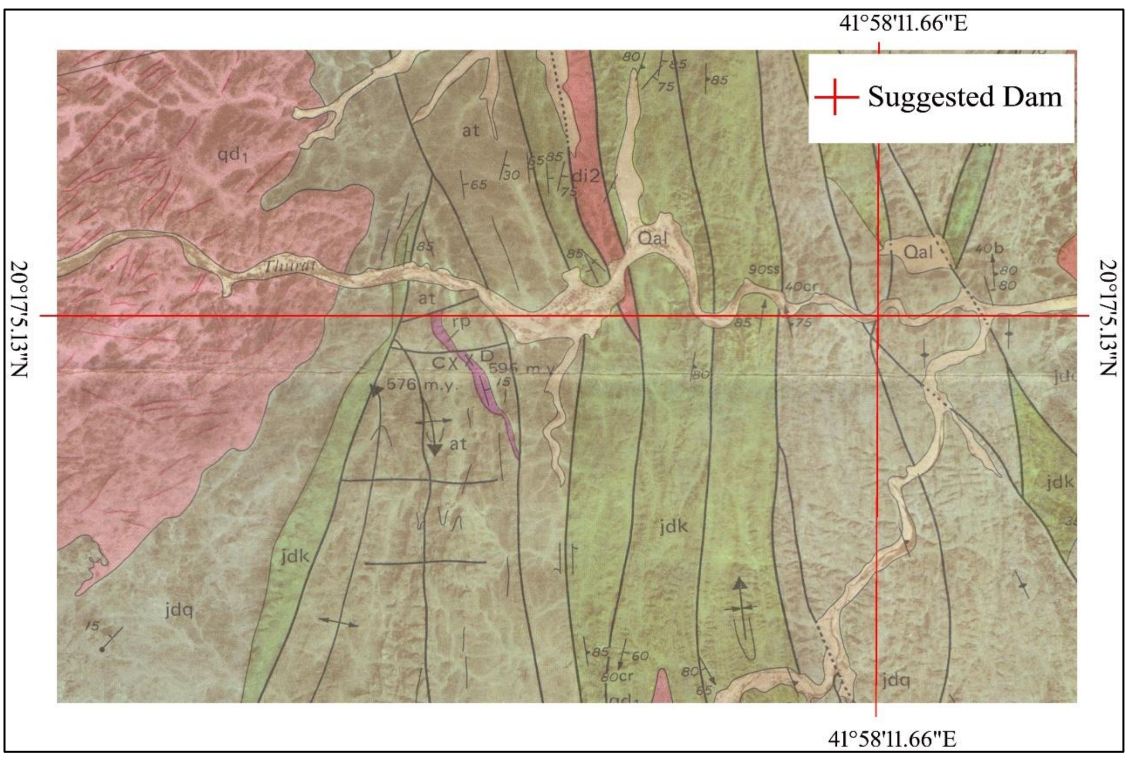


Figure C.2: Geological condition of suggested dam location in Al-Baha

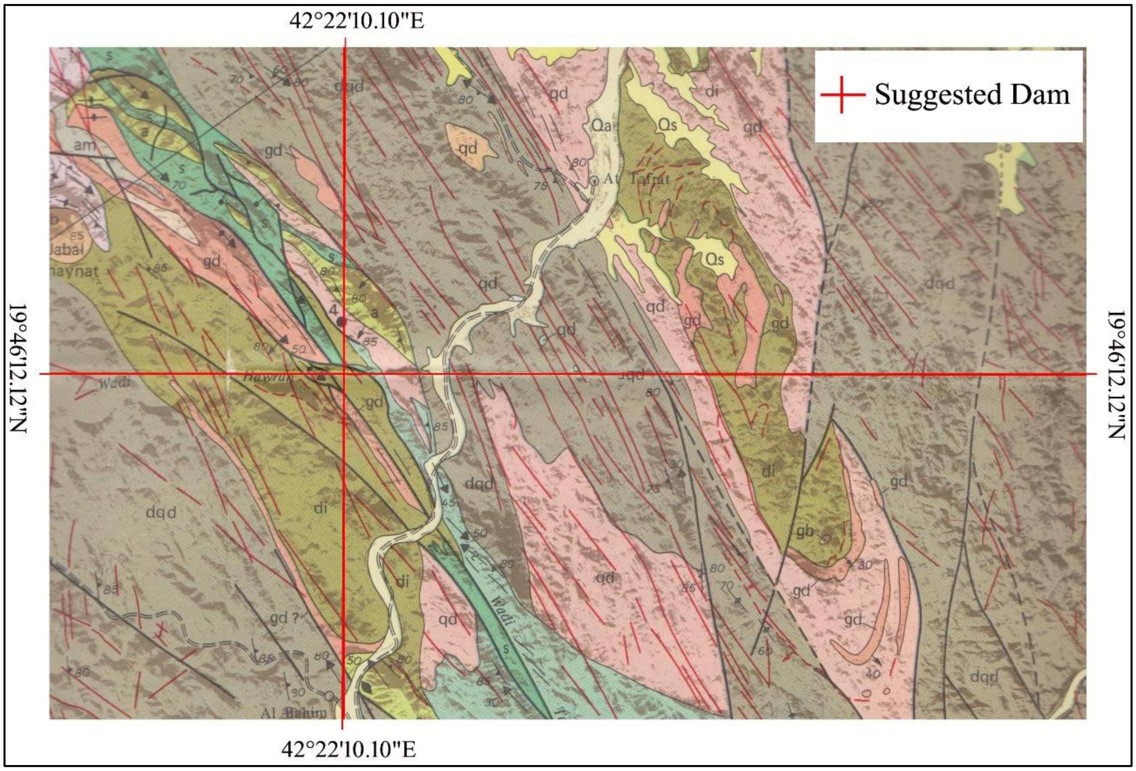


Figure C.3: Geological condition of suggested dam location in Bisha

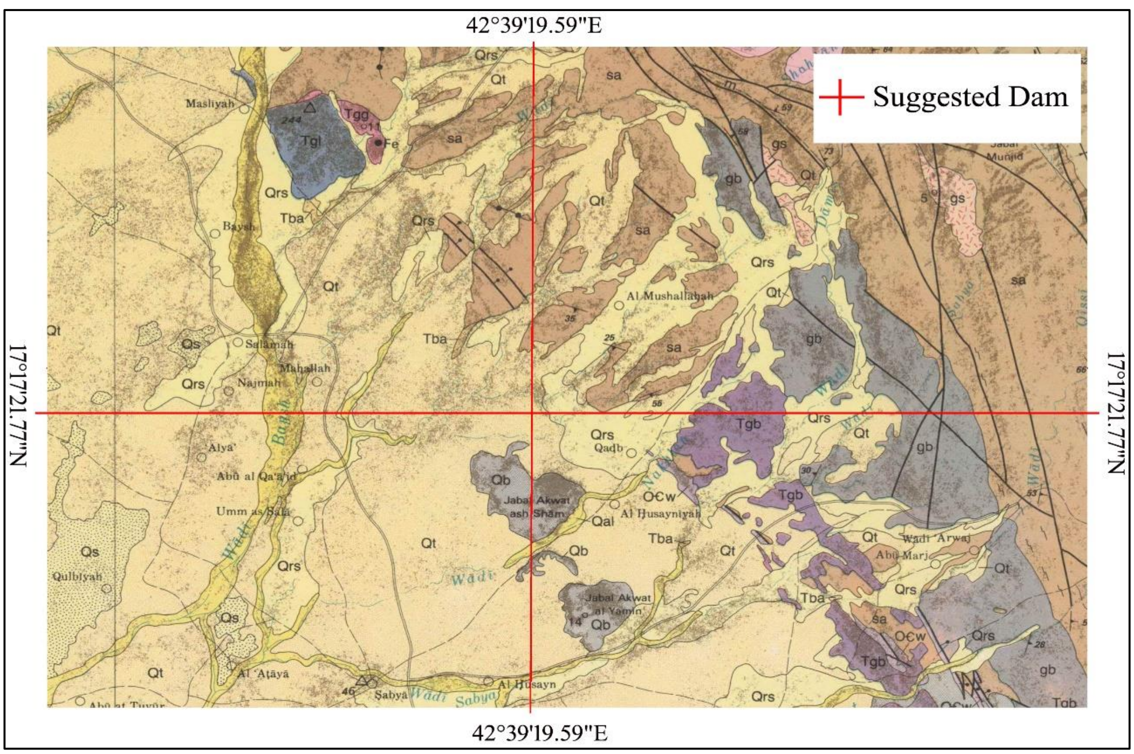


Figure C.4: Geological condition of suggested dam location in Jizan

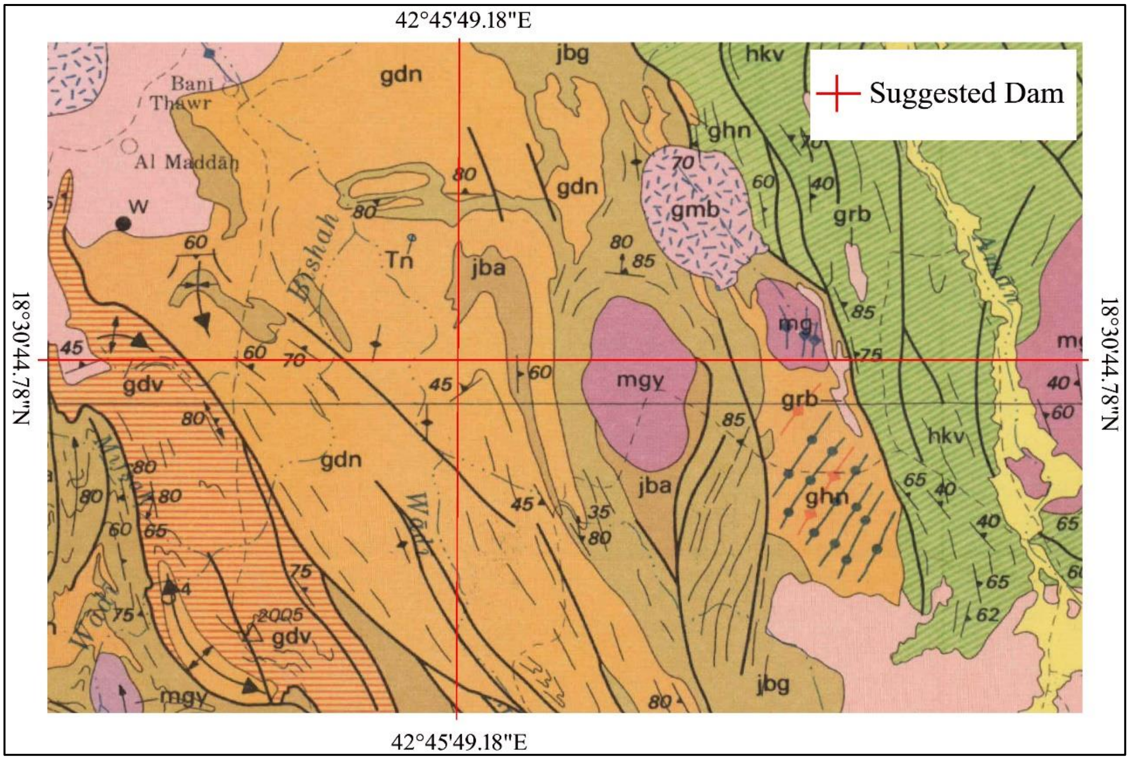
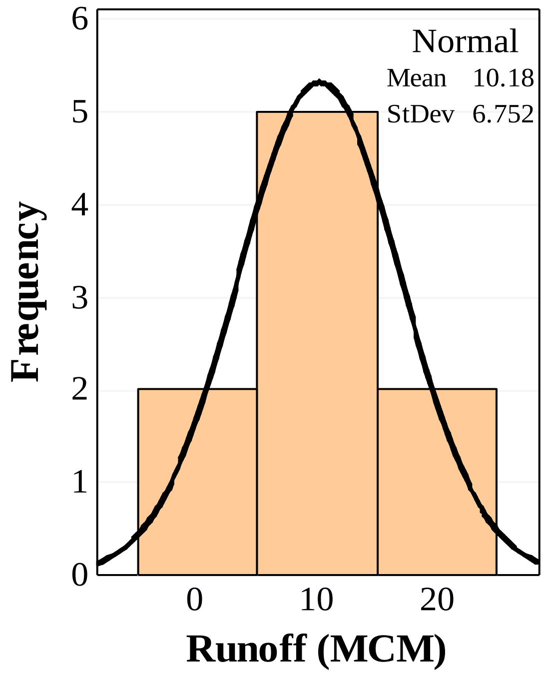


Figure C.5: Geological condition of suggested dam location in Khamis Mushait



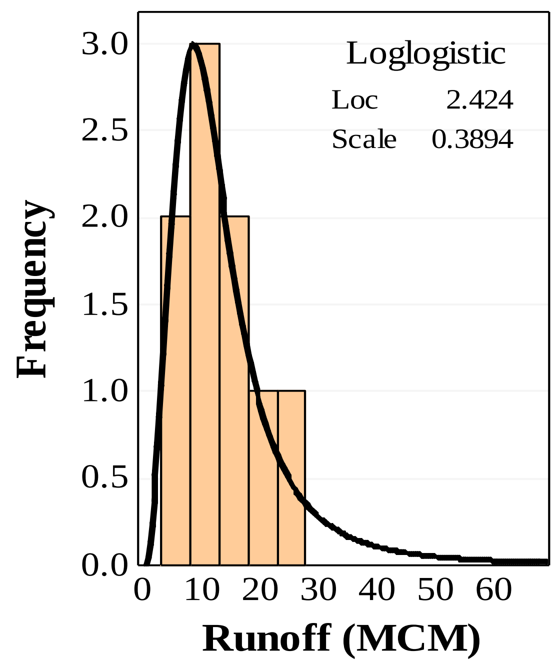
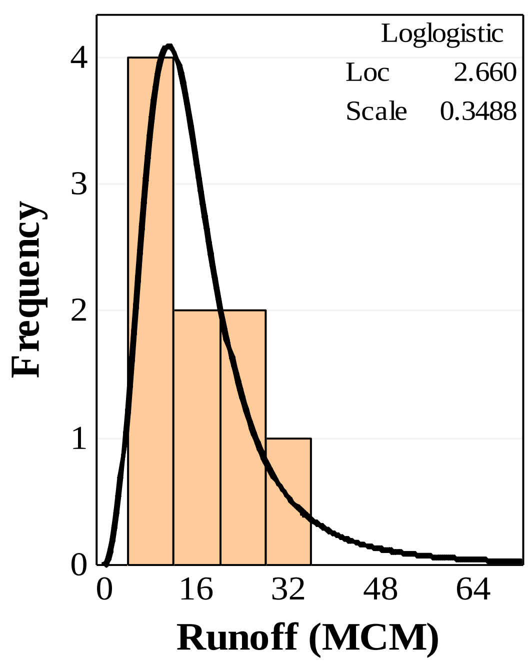


Figure C.6: Runoff distribution in Abha for 25-year return period

Figure C.7: Runoff distribution in Abha for 50-year return period



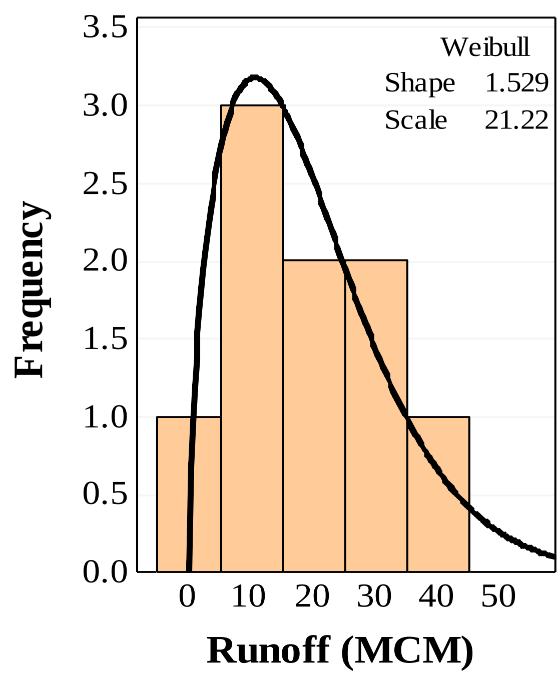


Figure C.8: Runoff distribution in Abha for100-year return period

Figure C.9: Runoff distribution in Al-Baha for 25-year return period

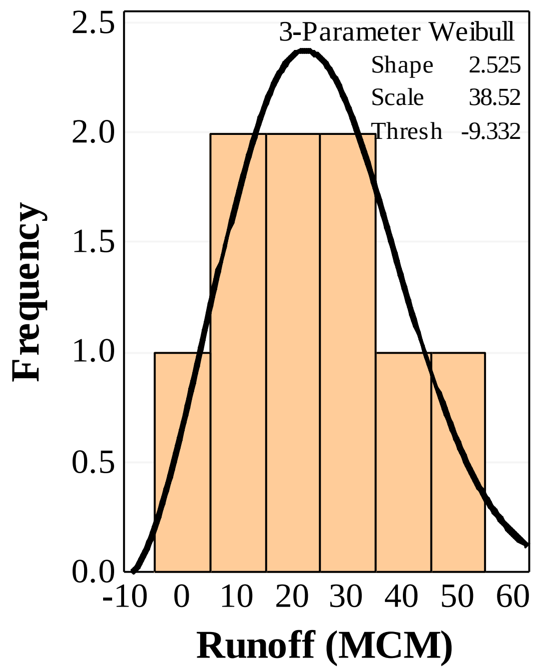


Figure C.10: Runoff distribution in Al-Baha for 50-year return period

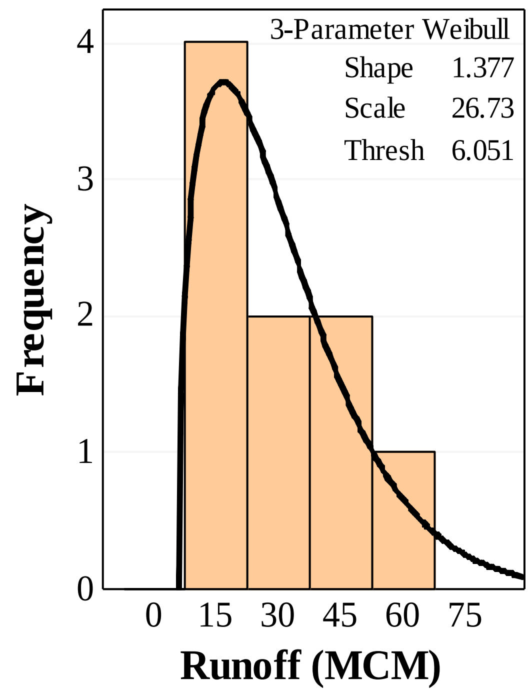


Figure C.11: Runoff distribution in Al-Baha for 100-year return period

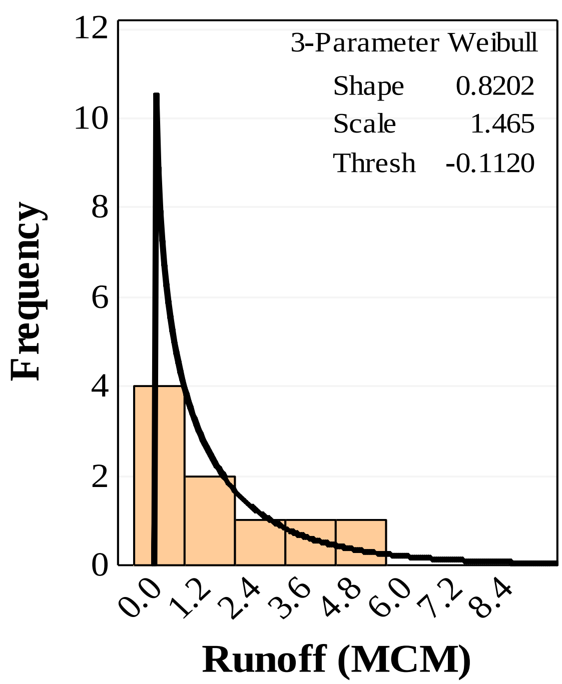


Figure C.12: Runoff distribution in Bisha for 25-year return period

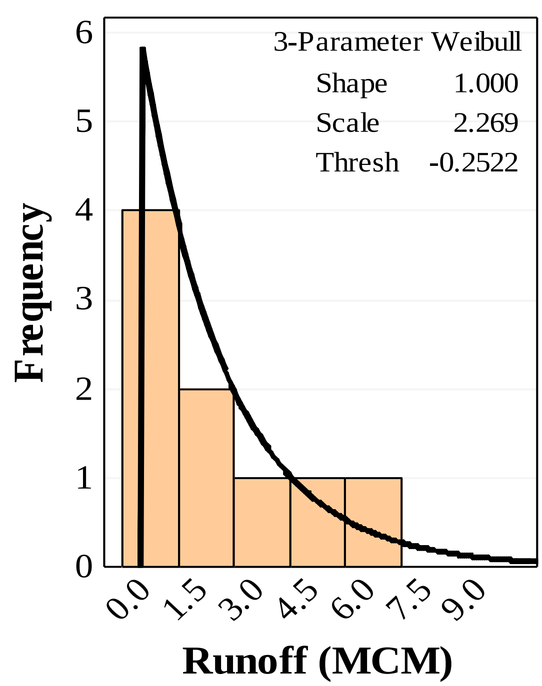


Figure C.13: Runoff distribution in Bisha for 50-year return period

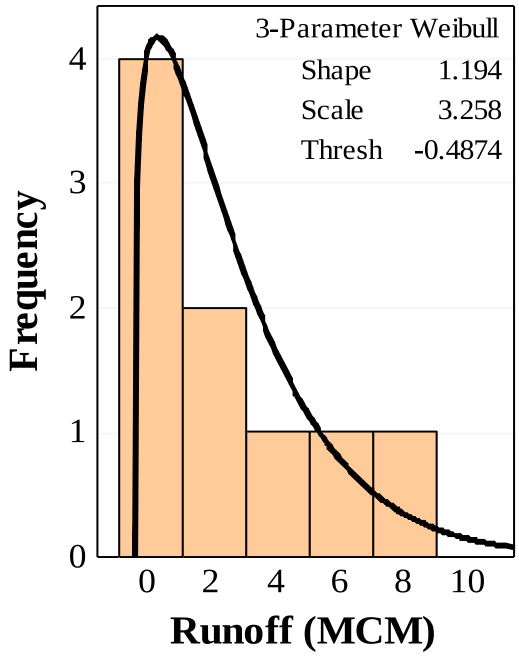


Figure C.14: Runoff distribution in Bisha for 100-year return period

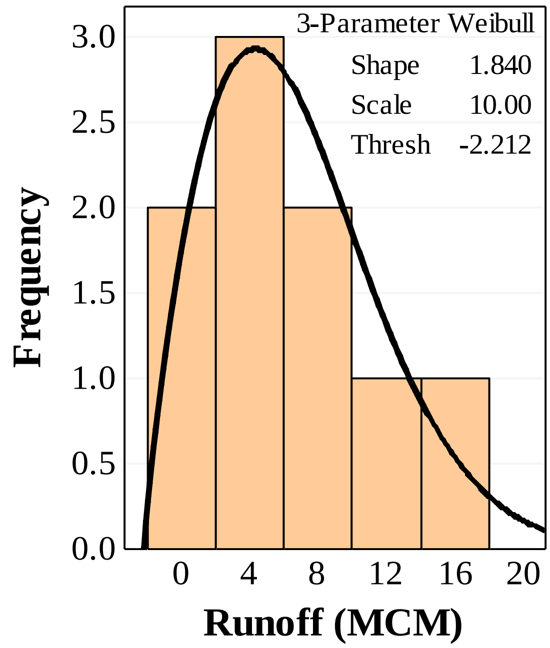


Figure C.15: Runoff distribution in Jizan for 25-year return period

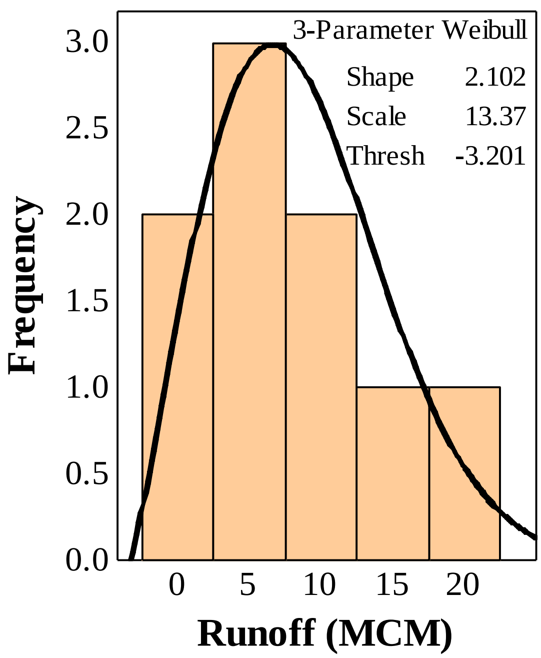


Figure C.16: Runoff distribution in Jizan for 50-year return period

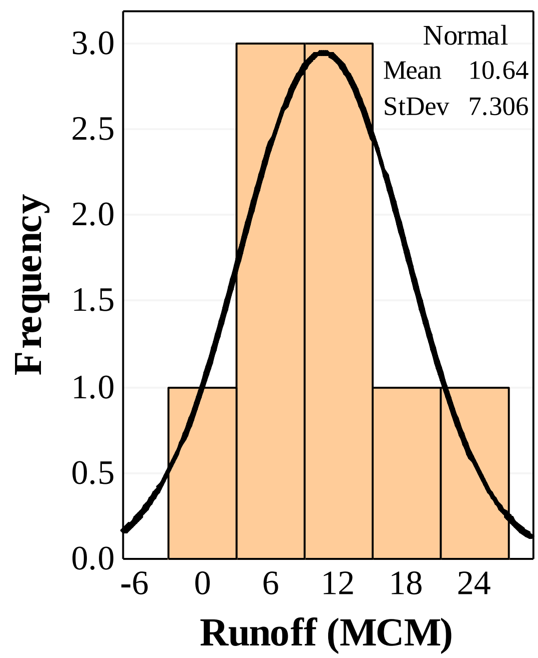


Figure C.17: Runoff distribution in Jizan for 100-year return period

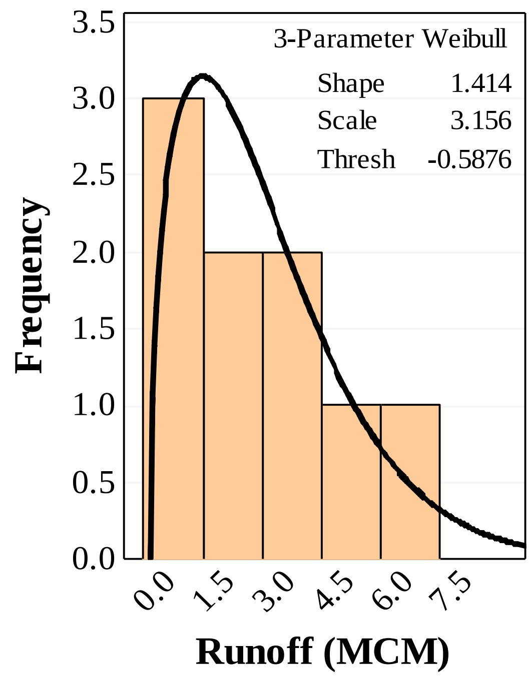


Figure C.18: Runoff distribution in Khamis Mushait for 25-year return period

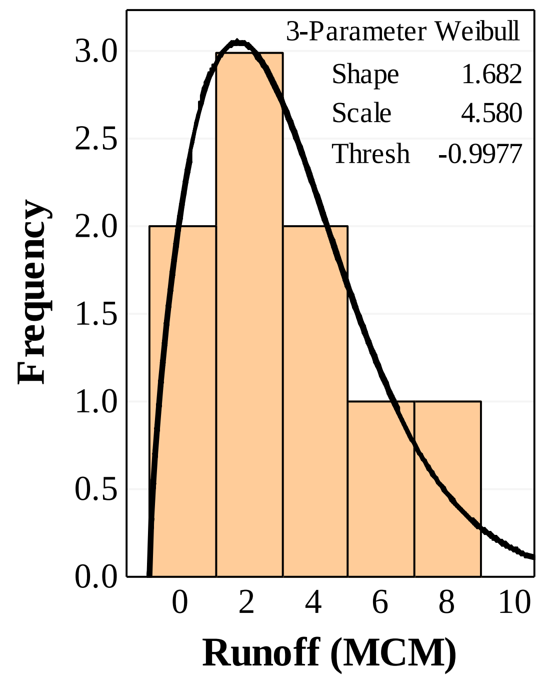


Figure C.19: Runoff distribution in Khamis Mushait for 50-year return period

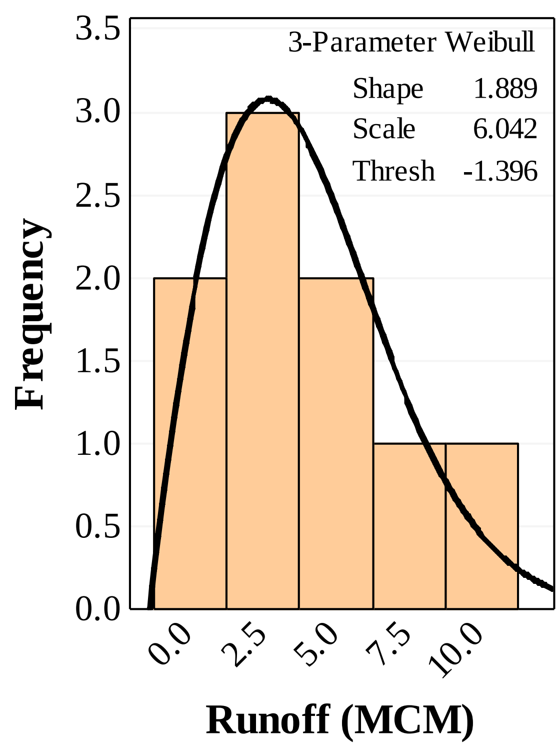


Figure C.20: Runoff distribution in Khamis Mushait for 100-year return period

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